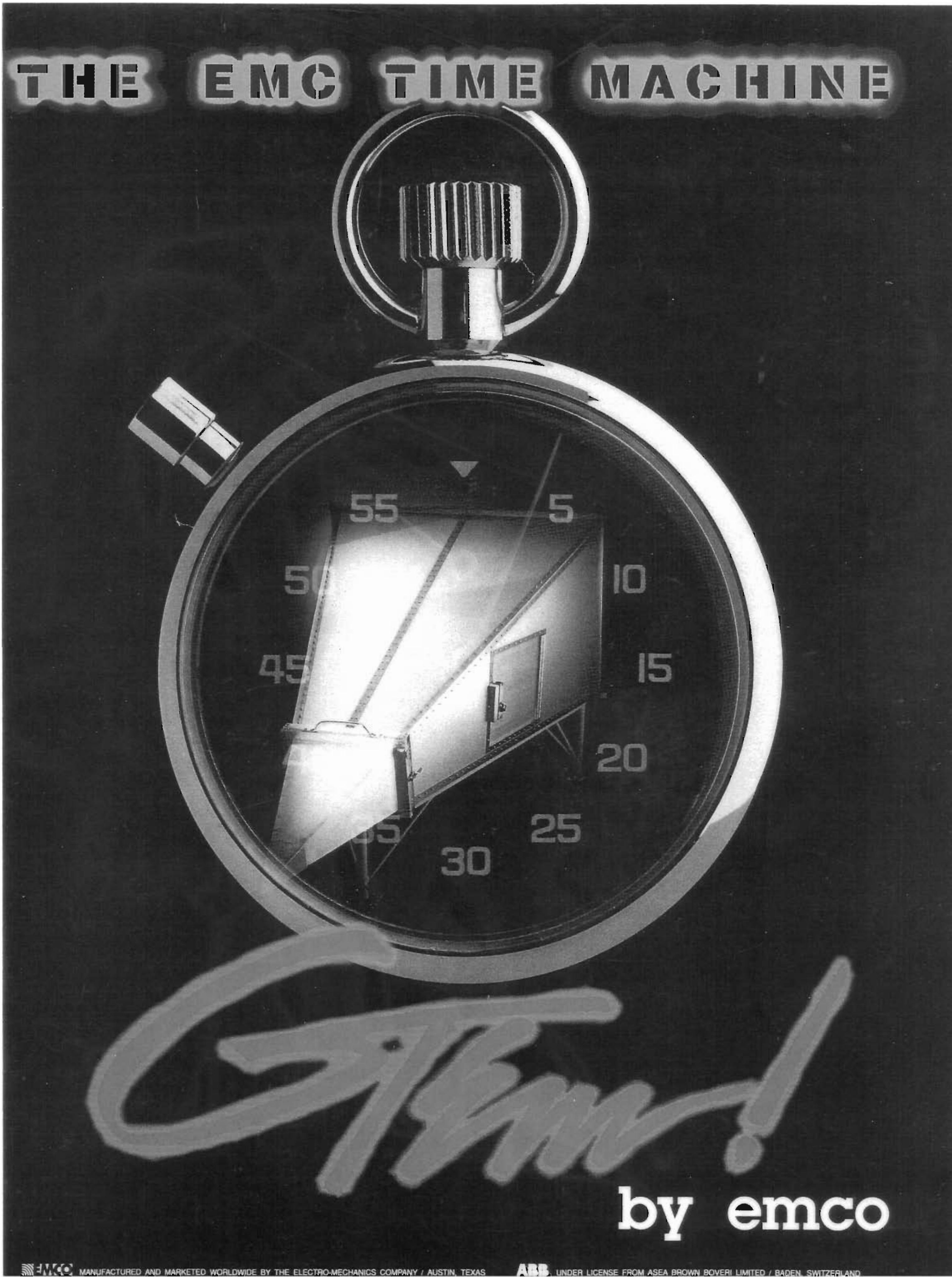
THE EMC TIME MACHINE
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GTEM!
by emco
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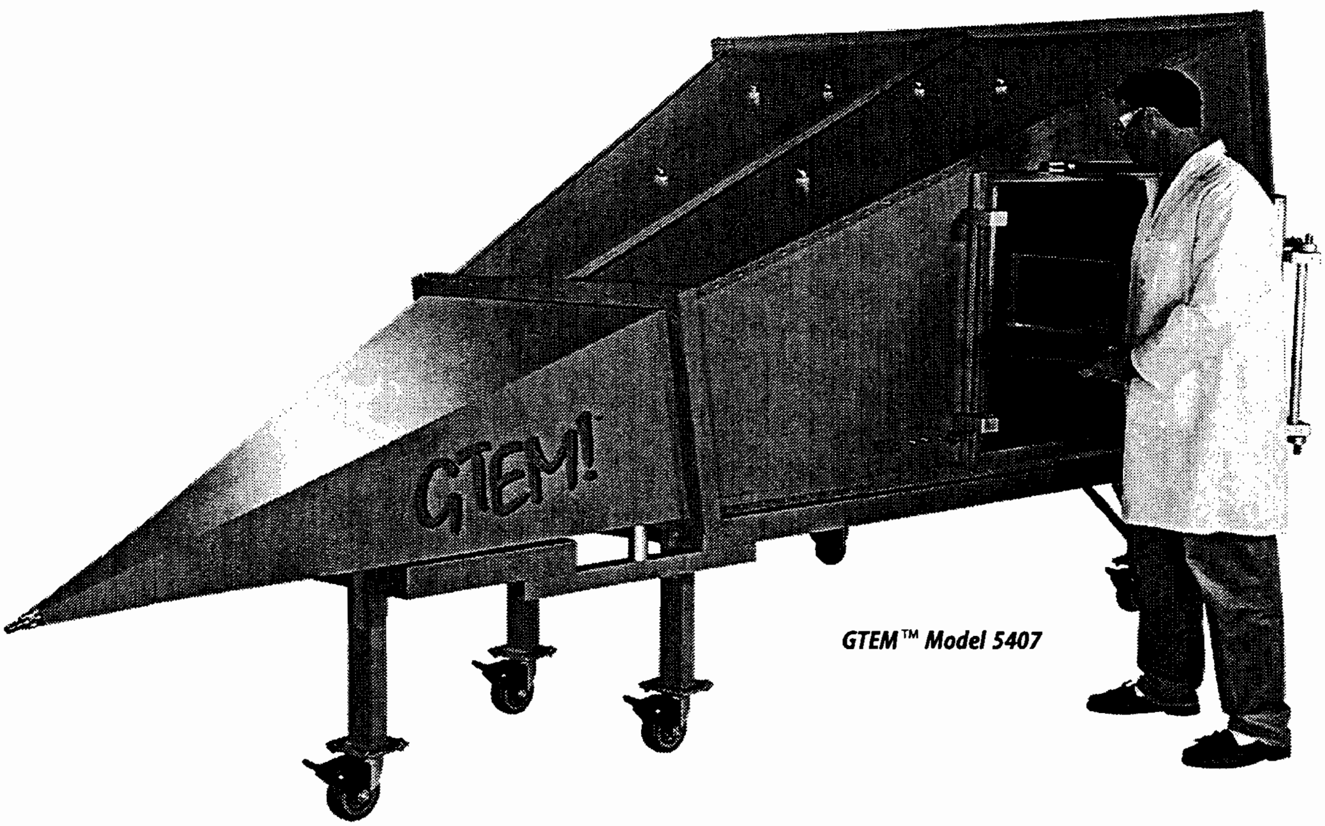
Operational Manual
Gigahertz Transverse Electromagnetic Cell (GTEM)

Model 5400 Series

5407
S/N 9903-1307



GTEM™ Model 5407

EMC TEST SYSTEMS, L.P. – An ESCO Company

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REV A - PN 399250

EMC Test Systems

Model 5400 Series

Gigahertz Transverse Electromagnetic (GTEM!™) Cell

Operation Manual

Copyright: 1998
Part Number: 399250
Revision: A

EMC Test Systems

Model 5400 Series

Gigahertz Transverse Electromagnetic (GTEM!™) Cell

Operation Manual

Introduction

General Description

The GHz Transverse Electromagnetic (GTEM™) Cell is a precision EMC test instrument primarily intended for use as an electromagnetic compatibility radiated immunity and radiated emissions test facility. It is intended for installation in a corporate, laboratory or industrial environment, where its unique characteristics allow fast, efficient conduct of electromagnetic compatibility (EMC) radiated tests at a convenient location, without impact of the ambient electromagnetic environment.

The GTEM is a pyramidally-tapered, doubly-terminated section of 50 ohm transmission line. At the input, a normal 50 ohm coaxial line is physically transformed to a rectangular cross section. The cross sectional dimensions are in a ratio of 3:2 horizontal to vertical dimensions. The center conductor, known as the septum, is a flat, wide conductor that when driven by a signal generator will produce a reasonably sized region of a nominally uniform electric field distribution underneath it. This region of nominally uniform field is the test volume for radiated immunity (susceptibility) testing. By the theory of reciprocity, radiated emissions testing is also conducted in the test volume. The septum is physically located well above the horizontal center line of the cross section, to increase the usable test volume, while maintaining constant characteristic impedance and uniform field distribution. The septum is physically terminated in a resistive array having a total value of 50 ohms for matching the current distribution on the septum. Test volume fields, either applied to an immunity test item or produced by the Equipment Under Test during emissions testing, are terminated in free-space foam RF absorber. Note the shape of the test volume is a tapered wedge. The fields generated by application of an RF voltage to the input of the GTEM propagate with a spherical wave front from the apex of the GTEM to the termination.

Acknowledgment

The GTEM is manufactured by EMC Test Systems, L. P., of Austin, Texas, in the United States of America, under license from Asea Brown Boveri Ltd., (ABB) of Baden, Switzerland.

GTEM Assembly

GTEMs are shipped in one or more plywood crates, or may be shipped partially assembled in certain circumstances. Large GTEMs are shipped in multiple crates. Figure 1 shows pertinent outer dimensions and floorspace requirements.

The EMCO Model 5407 GTEM is designed for easy assembly. Only common hand tools are required. The unit is shipped in four basic subassemblies. The subassemblies are: the feed section, rear (main) assembly, lower support section, and the front frame assembly. Due to the size of the shipping crates or the aforementioned assemblies, it may be sometimes necessary to ship the GTEM in smaller assemblies. In these cases, a factory technician or authorized designate will perform the installation.

Prior to starting the assembly, inspect the shipping crates for damage and move the crates to an open area. It is recommended that a forklift or other similar material handling equipment be used to move the crates. Remove the various parts from the crate. Before disposing of the empty crates, recheck the crates for parts to avoid accidentally disposing of valuable items. Familiarize yourself with the hardware provided to make the assembly process easier. All required hardware and fasteners is furnished with the GTEM.

Remove the wood shipping spacer from the front bars of the GTEM frame and the septum, as shown in Figure 2a. The shipping spacer maintains the septum placement during shipment. Mount the front frame assembly to the main assembly as shown in Figure 2b using the channel brackets to connect the two frames together.

Next place the feed assembly onto the front frame assembly. Align the frame on the feed assembly with the frame on the main assembly. The end of the septum in the feed section must slide under the septum in the main assembly, as shown in Figure 2c. If this septum lap joint does not align properly, it may be necessary to loosen the clamps of the printed circuit board assemblies (load boards) at the rear of the septum to allow movement of the main septum. If it is necessary to loosen these clamps, do not retighten the clamps until the center septum joint has been permanently connected.

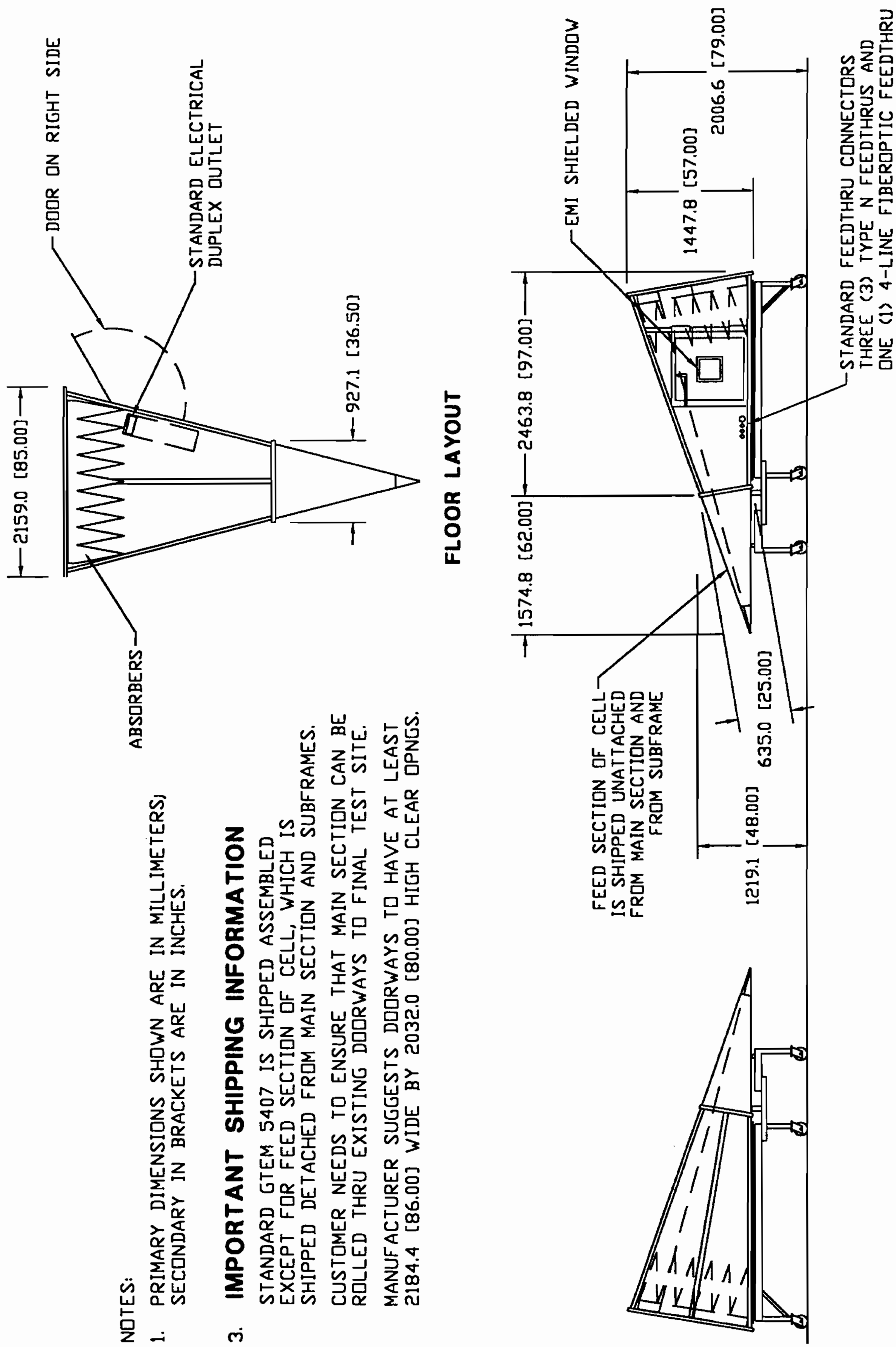

Figure 1. EMCO GTEM! Model 5407 assembly drawing with outer dimensions.

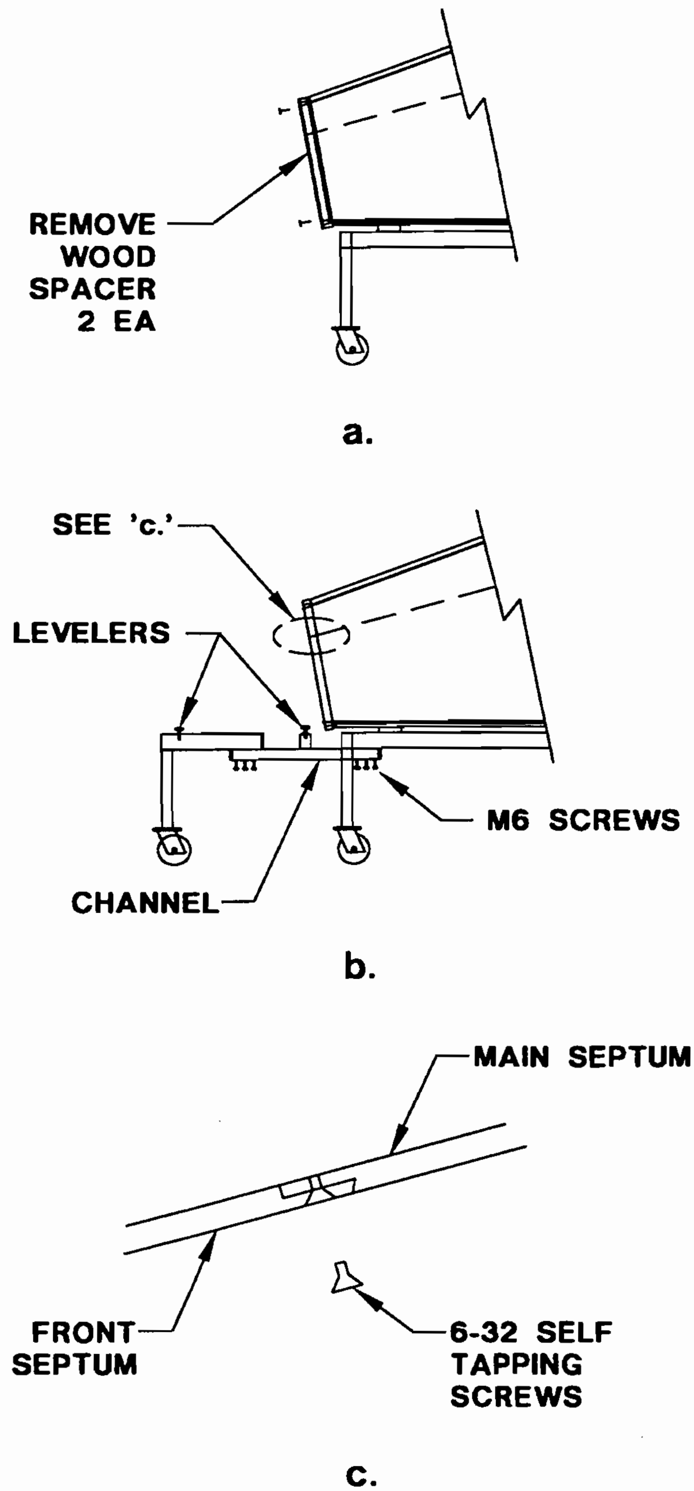

Figure 2. EMCO GTEM! Model 5407 assembly instruction drawing.

Install M6 pan-head phillips screws through frame of the feed assembly into the front bars of the frame on the main assembly. Use 6-32 flat-head self-tapping phillips screws (provided) to connect the septum joint together. To install the screws in the septum joint, the installer must climb into the GTEM to under the septum joint. The screws are installed from the bottom side of the septum joint. Assembly is now complete.

GTEM Specifications

GTEM specfications are shown on the next page in Tables I-II.

Basic Theory of RF Operation

In an RF sense, the GTEM is a very simple device. In principle the GTEM is a terminated transmission line, as far as basic analysis and theory are concerned. In practice, the actual electromagnetic field response is more complicated due to the flared walls and the hybrid resistor/absorber termination. There is a 50 Ω resistor termination for currents flowing on the septum, and an RF foam absorber termination for electromagnetic fields generated in the GTEM that are traveling towards backwall.

The GTEM as a Terminated Transmission Line

The GTEM is basically a section of asymmetric rectangular transmission line with a unique flared geometry and a hybrid termination. The RF response is similar to that of a terminated transmission line. An RF signal applied to the center conductor creates a uniform field directly below the flat septum, between the septum and the bottom of the TEM cell. Due to the geometry, there is a vertical and horizontal gradient in the electromagnetic field distribution inside the GTEM, just as there is in a coaxial transmission line.

Ideally the center one-third, both vertically and horizontally, of the volume below the septum is of sufficiently uniform distribution to allow use of the GTEM for immunity testing. In actuality, a test volume producing accurate results for radiated emissions testing may be as large as two-thirds of the vertical and horizontal dimensions. In the case of radiated immunity testing, the "uniform field" may not be as large, but it usually does exceed the one-third septum height by one-third cross-section width normally-listed value.

Since the GTEM provides a matched termination for input signals, there are no severe VSWR problems as is usually experienced with low-frequency biconical

TABLE I. GTEM Model 5400 Series Physical Specifications

	MODEL	OUTER CELL DIMENSION	APPROX CELL WEIGHT	DOOR DIMENSION	MAXIMUM SEPTUM HEIGHT	HIGHEST ACCURACY TRANSVERSE TEST SURFACE IN CENTER OF CELL	DISTRIB LOAD RATING	
	5407	(L) 4.0 m (13.1 ft) (W) 2.2 m (7.1 ft) (H) 2.1 m (6.8 ft) w/ base (H) 1.4 m (4.6 ft) w/o base	500 kg 1100 lb	(W) 686 mm (27.0 in) (H) 747 mm (29.4 in)	900 mm (35.4 in)	(W) 400 mm (15.8 in) (H) 400 mm (15.8 in)	430 kg 950 lb	

TABLE II. GTEM Model 5400 Series RF Electrical Specifications

	MODEL	FREQUENCY RANGE	VSWR TYPICAL	MAXIMUM CW INPUT POWER	INPUT IMPEDANCE	FEED CONNECTOR TYPE	SHIELDING EFFECTIVENESS	
	5407	RE TESTS[1] 9 kHz - 5 GHz RI TESTS[2] DC - 20 GHz	CHARACTERISTIC FREQ 1.5:1 ≥ ALL OTHER FREQ 1.5:1 ≥	200 W 500 W w/ opt. blower	50 Ω	CW 7/16 DIN plug to N jack adaptor	From internal E-fields 80 dB minimum 10 kHz - 1 GHz	

class antennas. It is relatively easy to produce low frequency intense electromagnetic fields with the GTEM. In fact, using summing techniques, emulations of complex electromagnetic environments are possible. The capability of a GTEM to operate without size or scaling problems well into the GHz frequency range allows the testing of items without the need for frequent antenna changes. The low VSWR allows the generation of a test electromagnetic environment for frequencies well in excess of 1.0 GHz.

Characteristic and Wave Impedances of a GTEM

For basic analysis purposes the GTEM may be considered as a special case of a coaxial transmission line. The characteristic impedance of the GTEM is set by its internal dimensions, namely the width of the septum and its location, in combination with the cross sectional dimensions. Since it is an asymmetric transmission line, the derivation is complicated, but follows the same approach as that used for a coaxial transmission line. For brevity and simplicity, the derivation of the impedances of a coaxial line is shown, instead of that of a GTEM Numerous literature references describe TEM and GTEM cell characteristic impedance calculation; contact the factory for details if interested.

A traditional coaxial transmission line, with inner conductor of radius *a* and outer conductor with inner radius *b*, has per unit length values of capacitance and inductance given by the equations

$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)},\ L = \frac{\mu_0}{2\pi}\ln(b/a),$$

where ε_0 and μ_0 are the permittivity and permeability of the material between the conductors, assumed free-space in what follows. The coax transmission line characteristic impedance is given by the equation

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{\ln(b/a)}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}} = 60\ln(b/a)$$

The magnitude of the electric and magnetic field strengths between the conductors are given by the equations

$$E = \frac{V}{\rho\ln(b/a)},\ H = \frac{I}{2\pi\rho}.$$

Here V is inner conductor voltage, I is inner conductor current, and ρ is distance from center. The field or wave impedance is given by the ratio of *E/H*, or

$$\eta = \frac{E}{H} = \frac{V}{\rho \ln(b/a)} \frac{2\pi\rho}{I} = \frac{V}{I} \frac{2\pi}{\ln(b/a)}.$$

But V/I is Z_0, then substituting in from Z_0 above gives

$$\eta = Z_0 \frac{2\pi}{\ln(b/a)} = 60\ln(b/a)\frac{2\pi}{\ln(b/a)} = 120\pi.$$

Note that the value of the ratio of *b/a* can be selected to give a characteristic impedance of 50 Ω, while the wave impedance 377 Ω between the conductors. This is a condition for transverse electromagnetic mode (TEM) operation. While the geometry and the calculations are more complex, the same conditions hold true for the GTEM, that is the characteristic impedance of the GTEM is set by the cross-sectional dimensions to 50 Ω, while maintaining TEM operation with wave impedance values of 377 Ω.

Termination Characteristics

Having derived the transmission line characteristics of a coaxial transmission line, it is postulated that the characteristics of a GTEM match those of the coaxial line. The characteristic impedance is 50 Ω, and the TEM mode exists. The next step is description of the termination performance. It was stated above that the GTEM is a doubly-terminated or hybrid-load device. The two terminations are:

1.) Resistive to match the currents flowing in the septum, and

2.) RF absorbers to "terminate" (absorb) electromagnetic fields propagating to the termination.

The performance of these two terminations separately and in combination are discussed below.

Load Boards - The GTEM employs printed-circuit boards to hold a large number of resistors that compose the resistive termination. At low frequencies, where the match of the load boards is excellent, the return loss of the GTEM is that of the load boards by themselves. As frequency increases, the resistive distribution parasitic elements degrade performance, as does the parallel

termination of the RF absorbers that appears as a capacitive element, causing the return loss to increase.

RF Absorber - The second part of the GTEM hybrid termination is the array of RF absorbers. At low frequencies, the RF absorber shows very poor return loss. As frequency increases, however, the RF absorber match improves until the return loss due to the absorber is quite low.

Combined Performance - From a transmission line perspective, the two terminations act in parallel. The load boards dominate the response at low frequencies, while the RF absorbers dominate the response at higher frequencies. The transition between the responses shows as an increase in the return loss at what is called the critical, characteristic, or termination crossover frequency of the GTEM. This critical frequency is seen as an increase in the VSWR of the GTEM. The critical frequency depends on the size of the GTEM and the volume of absorber.

Measured GTEM Performance

There are several different measurable quantities that illustrate the performance of a GTEM. Typical measurements are discussed in this section.

GTEM Performance Quantification - VSWR

The Voltage Standing Wave Ratio (VSWR) of a terminated transmission line is a fundamental performance parameter. Since the value of the VSWR reading is a measure of mismatch, it completely defines the capability of a GTEM to transfer power from interconnected 50 Ω RF test equipment. The VSWR is a qualifying measurement for GTEMs. Most GTEMs are pre-assembled at the factory and the VSWR is verified. VSWR of a typical GTEM Model 5407 is shown in Figure 3. VSWR was measured with an HP8753C vector network analyzer.

GTEM Electromagnetic Field Response

Electric Field Frequency Response - The E-field frequency response is defined as electric field strength at a specific point in the GTEM measured with or normalized to a constant forward input power. Figure 4 shows a typical Model 5407 TEM mode or vertical electric field frequency response normalized to 10 W constant forward power at a center point where the septum height is 80 cm. At other locations electric field frequency response can vary from this by several dB.

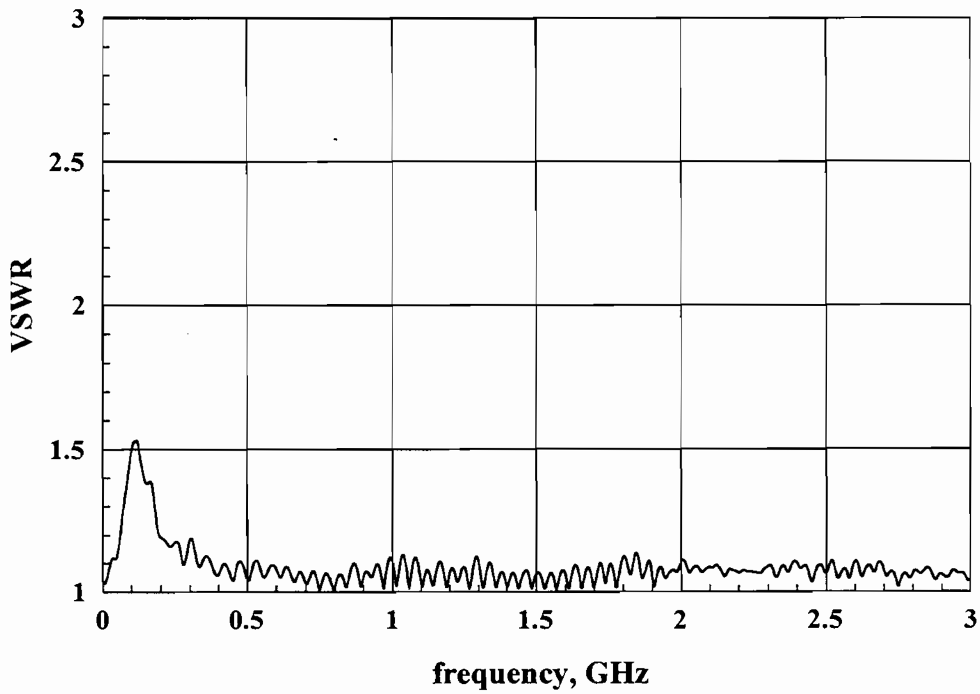

Figure 3. Typical EMCO GTEM Model 5407 VSWR.

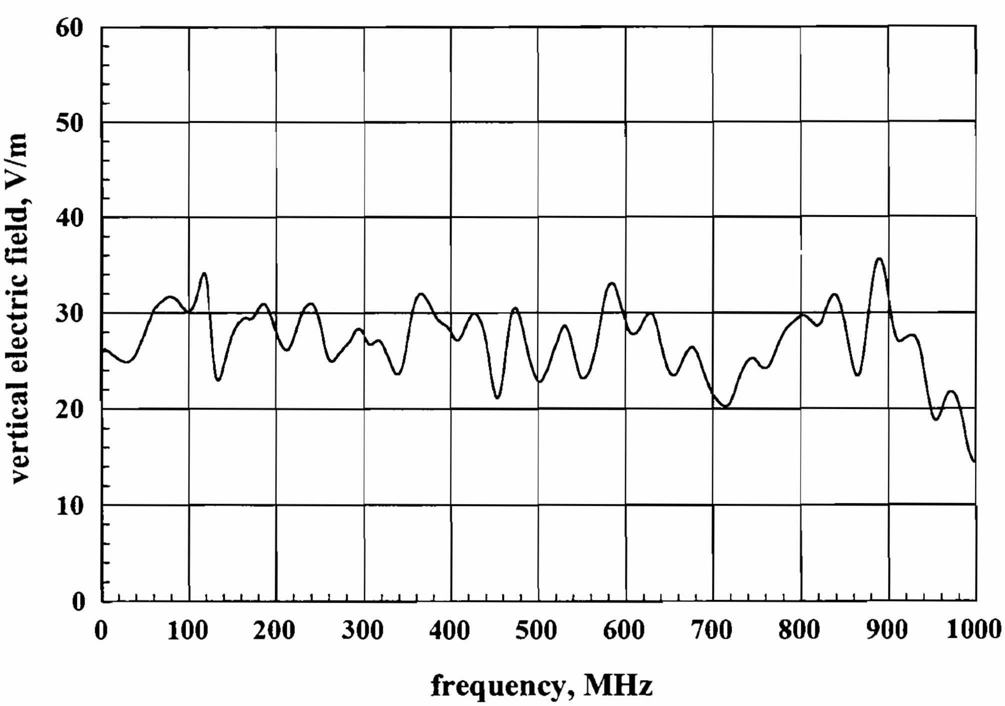

Figure 4. Typical EMCO GTEM Model 5407 electric field frequency response for 10 W constant forward power at 40 cm above floor and 80 cm septum height.

Electric Field Uniformity - The electric field uniformity of a GTEM at a given frequency is defined as the maximum difference in dB between measured electric field at various spatial locations and electric field at a reference location. Following EN61000-4-3-1997 and Annex D contained therein, uniformity is defined and measured over a transverse "calibration" plane in the GTEM cross-section. At each frequency, the reference location can be arbitrarily chosen, for example the center or bottom corner point of the calibration plane. After performing the plane calibration in the empty GTEM, the EUT is inserted with its front face coincident with the calibration plane. As of this writing, a draft amendment to IEC 61000-4-3 is being considered which better defines how to perform field calibrations in TEM devices.

The electric field uniformity of a GTEM Model 5407 as measured according to EN61000-4-3-1997 requirements is shown in Figure 5. Nine spatial points were measured in a 40 x 40 cm^2 vertical plane centered at a 80 cm septum height. The standard allows 25% of the points to be omitted at each frequency; at least seven of the nine points fulfill the -0, +6 dB criteria as required.

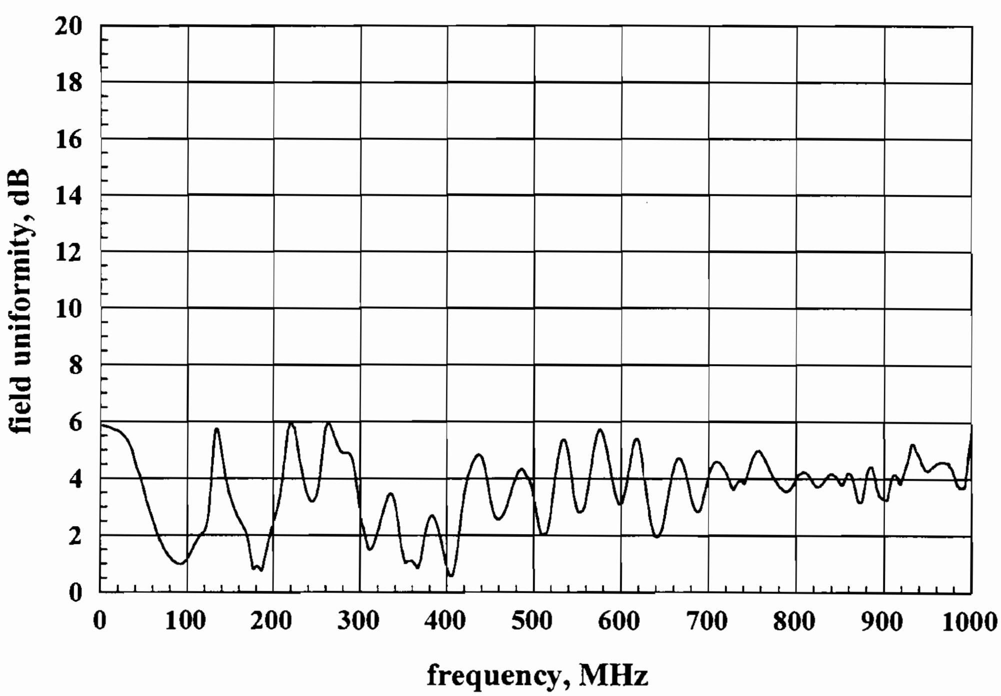

Figure 5. Typical EMCO GTEM Model 5407 field uniformity, 40 x 40 cm^2 transverse plane, 80 cm septum height.

GTEM Shielding Effectiveness (SE)

The shielding effectiveness of a GTEM is difficult to measure by conventional IEEE-299-type methods, due to GTEM size and the flared walls. Alternative methods have been developed, eg. [1]. The primary technical issue is the choice of reference signal for the SE tests. Due to size constraints, normal antennas cannot be used to generate the signal inside the GTEM. In addition, electric field intensity along the GTEM can vary more than 20 dB from apex to load. For these reasons, a modified two-antenna swept-frequency procedure was used to measure SE of the Model 5407. In this method, power is input into the GTEM as in a normal immunity test, and the receive readings of two loop probe antennas, one inside and the other outside the GTEM walls, are compared. For the Model 5407, a >80 dB specification SE was verified with this method.

GTEM Emissions Testing Characterization

A representative radiated emissions comparison of a GTEM measurement to an OATS Measurement is reported in detail in the paper included in Annex B.

GTEM USE

The intended use of the GTEM is radiated immunity testing and radiated emissions testing. The following sections on GTEM usage provide a general overview of these uses. Note that the test operator must plan and implement the testing of all devices as thoroughly as in any facility to assure repeatable results.

Radiated Immunity Testing

Radiated immunity testing is conducted to ascertain if the equipment under test (EUT) will respond to radiated energy in the electromagnetic ambient in a deleterious manner. The GTEM provides an ideal facility for the accomplishment of such tests in a laboratory environment. Immunity (susceptibility) testing is straightforward. Simply connect the output of a 50 Ω power amplifier to the input of the GTEM. The standard RF power handling capability of the GTEM 5407 is in excess of 200 W. Greater power handling capabilities are possible if modified load boards or optional blowers are installed. Field intensities in excess of 200 V/m can be generated with sufficient power.

Estimation of GTEM RF Input Power Required for a Given Field Strength

Estimation of the power required for obtaining a given field strength is easy. Using the parallel-plate electric field approximation, the estimated field strength

halfway between the septum and the floor of the GTEM is given by the ratio of the RF voltage on the septum to the spacing of the septum above the GTEM floor, or

$$E \text{ (Volts/metre)} = V \text{ (Volts)} / h \text{ (metres)}$$

RF voltage is obtained from the drive power by the equation

$$P_{in} \text{ (Watts)} = V^2 \text{ (Volts}^2\text{)} / Z_0 \text{ (Ohms)}$$

where P_{in} is input RF Power (Watts), V is RF voltage on the septum at height h, and Z_0 is the GTEM characteristic impedance (50 Ω). Then a simple solution is

$$E = (1/h)\,(P \times Z_0)^{1/2} \;,\quad P = (E\,h)^2 / Z_0$$

The equations above can be used for first order estimates of field strength given power, or power required for a given field strength. Power required calculated by this method is approximate, and actual power needed for a given electric field strength will vary versus frequency and location in the GTEM. Typical measured power required for 10 V/m at a 0.8 m septum height in a Model 5407 is shown in Figure 6.

Figure 7 shows a typical setup for the conduct of radiated immunity testing using automated control techniques. Testing can be completely automated if it is possible to define a test signal response from the EUT which can be sensed by the controlling computer. A signal generator is shown with an external modulation source so that the modulation characteristics can be matched, if desired, to signals internal to the EUT. The output of the signal generator is applied to a RF power amplifier, which in turn drives the GTEM. Application of the signal to the GTEM input produces the test signal between the septum and the floor of the GTEM. Internal to the GTEM, an optional broadband, high-level isotropic probe monitors the level of the applied signal. With an EMCO 7110, one to eight probes with individual metering units may be used to sense the applied field at different locations and report actual electric field strength values.

The EUT is installed in the GTEM in the approximate center of the test volume. Monitoring of EUT performance is via a cable to any externally located monitor unit. Typical precautions must be taken, such as are used in shielded enclosure immunity testing with EUT performance monitors. An example would be grounding the shield of the cable to the performance monitor to the bottom of the GTEM. Once the setup is complete, the signal generator is tuned over the test frequency range while monitoring the performance of the EUT for response to the

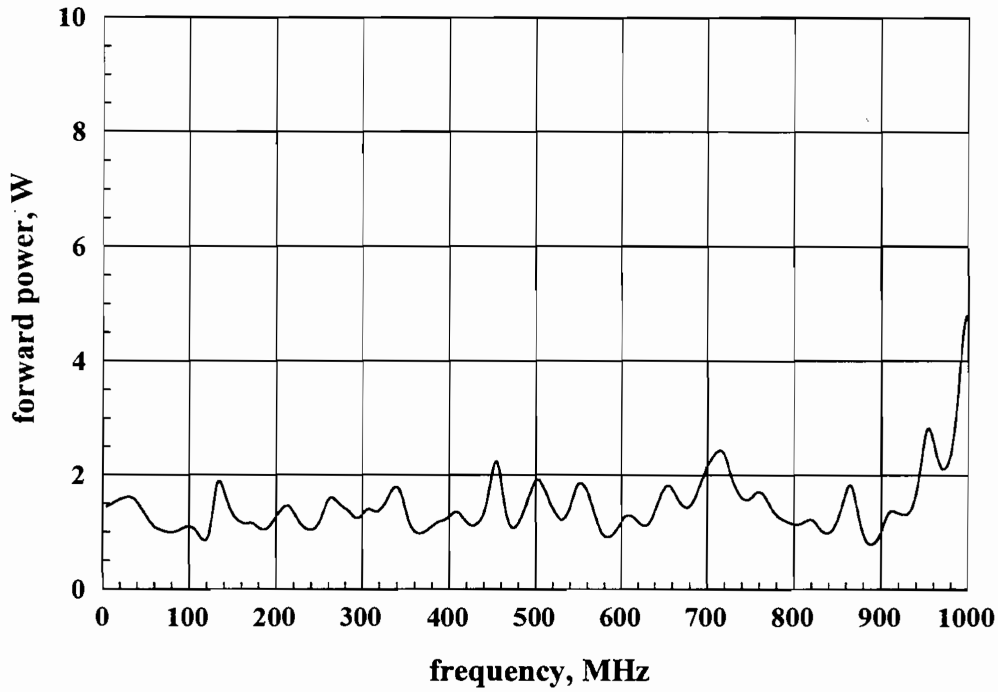

Figure 6. Typical 10 V/m power required in EMCO GTEM Model 5407 at 40 cm height above floor and 80 cm septum height.

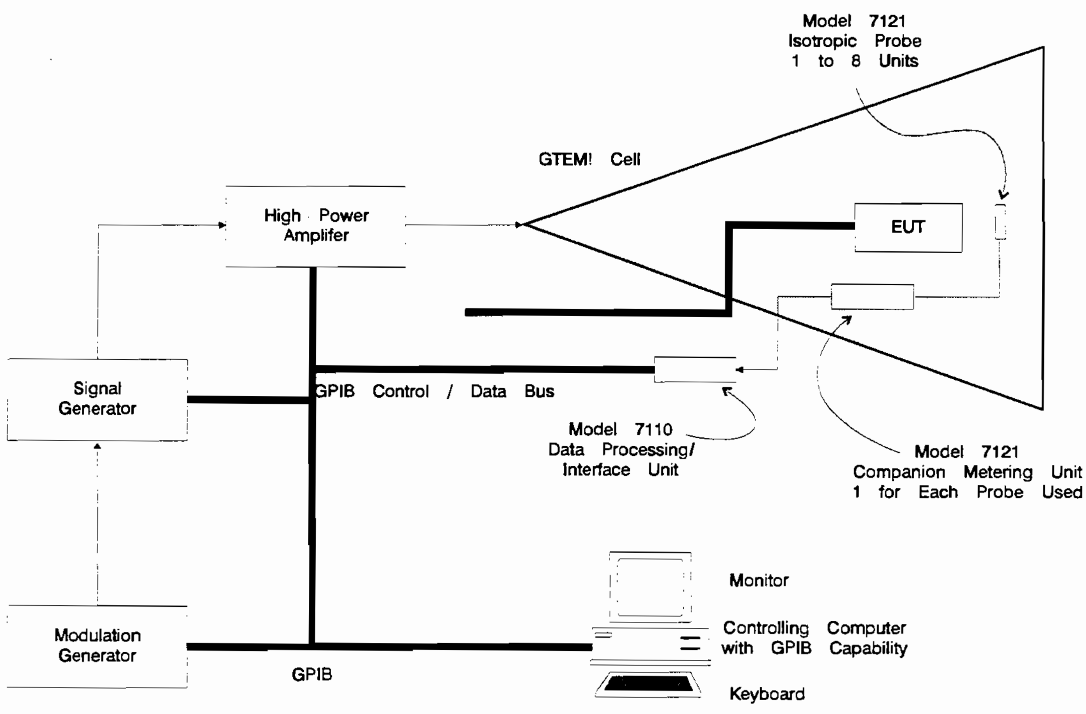

Figure 7. Typical automated radiated immunity test setup.

applied test signal. The levels of the test signal are adjusted by controlling the signal generator output while monitoring for the minimum field level at the location of the isotropic probes.

Note that the electric field strength and the sweep speeds are often set by the test requirements document(s). Care should be taken to not exceed specified sweep speeds. An additional factor is that, with the availability of automated testing, it is possible to sweep at the specification-required speed without consideration of the performance of the EUT. If the EUT must be stepped through a number of modes at "each frequency" then even slower sweep speeds may be needed.

Radiated Emissions Testing - General

In addition to immunity testing, the GTEM may be used for radiated emissions testing. An item placed in the test volume under the septum can be evaluated for radiated emissions as easily and as simply as an immunity test is accomplished. By the reciprocity principle in electromagnetic theory, if the application of a RF voltage generates a field, then the introduction of a device that radiates a field in the volume under the septum will produce an RF voltage at the GTEM input connector. The voltage produced will be proportional to the intensity of the radiated field.

Only recently has the use of the GTEM as an alternative to radiated emissions measurements on an OATS been seen as a practical choice. The main development that brought the GTEM forward as a practical radiated emissions device was the three-position correlation algorithm (derived by Wilson et al. at ABB, based on results from NIST), which allowed the direct comparison of data taken in a GTEM to data acquired on an OATS. The GTEM feed connector voltages produced by radiated emissions from the EUT at each of three orthogonal positions are measured. Then at each frequency, an equivalent set of dipole antennas that would produce the same voltages at the GTEM connector are defined via computer computation. Once these equivalent antennas are defined, the field intensities for comparison to the given specification limit are computed from the set of equivalent dipoles at each frequency, given the separation and geometry of the test setup on an OATS.

The simplest GTEM to OATS correlation algorithm uses three EUT positions. Various other rotation schemes have been described in the literature; contact the factory for details if interested.

Radiated Emissions Measurements

Hardware Requirement - Measurement of radiated emissions requires the use of a frequency-selective EMI Meter or spectrum analyzer. For manual use, any calibrated receiver typically used for EMC measurements is acceptable as long as the test specification requirements for the measurement device are met.

EUT Orientation for Testing - Proper orientation of the EUT in three orthogonal axes is necessary for the accurate conduct of radiated emissions measurements. To perform the EUT rotations, separate coordinate axes are defined for the GTEM and the EUT. The mathematical model for the correlation to an Open Area Test Site (OATS) and the need of the three orthogonal rotations is described in Annex A of this manual, *Theory of GTEM Correlation.*

The three reference orthogonal axes of the GTEM are normally defined as the positive **Z** axis is to the feed, the positive **Y** axis is up, and the positive **X** axis is toward the right of the cell as seen from the apex. Note that this is a positive right-handed rectangular coordinate system, i.e. **X** rotated into **Y** in a **right-handed** sense gives a positive **Z**. In this discussion the primary reference axes of the GTEM will be denoted by capitol letters **X, Y, Z.** The EUT also has right-handed axes, denoted as **x, y, z.**

The mathematical formulation of the GTEM model for determining the OATS-equivalent value of radiated emissions requires three measurements of voltage produced by the EUT in three orthogonal axes positions. In the rotation scheme, the three positions must permute the axes, or the axes must align as follows:

Position 1	GTEM axes	**X Y Z**
	EUT axes	**x y z**
Position 2	GTEM axes	**X Y Z**
	EUT axes	**y z x**
Position 3	GTEM axes	**X Y Z**
	EUT axes	**z x y**

In position 1, the EUT axes are aligned or coincide with the GTEM axes as shown in Figure x. The EUT array, a PC system installed on a plywood panel per the requirements of ANSI 63.4-1992, is shown with the **x**, **y**, **z** EUT axes aligned with the **X**, **Y**, **Z** GTEM axes. Note that the EUT and GTEM axes are shown in alignment at the top, right sides, and bottom of Figure 8. At the bottom of Figure 8 the circle with the dot at the center represents the tip of the axis arrowhead pointing out of the page.

In position 2, the EUT is rotated in a manner such that the **y** axis aligns with the **X** axis, the **z** axis aligns with the **Y** axis and the **x** axis aligns with the **Z** axis. Figure 9 shows the alignment of the GTEM and EUT axes for this rotational position.

In position 3, the EUT has been rotated in a manner such that the **z** axis aligns with the **X** axis, the **x** axis aligns with the **Y** axis and the **y** axis aligns with the **Z** axis. Figure 10 shows the third position, again as seen from the apex of the cell.

Measurement Procedure - The following general procedure should be used to perform radiated emissions measurements in a GTEM This procedure is written for manually performed measurements.

1. Install the EUT in the center of the test volume of the GTEM with a reference orientation, as shown in Figure 8 and as described above for the first position.
2. Measure the RF voltages emanating from the EUT as a function of frequency over the desired frequency range. Depending on the measurement device used, either peak, quasipeak, or average measurements may be made. These measurements are collectively referred to as V_{xyz} versus frequency.
3. Rotate the EUT through two successive 90^{o} right hand rotations, such that the **x** axis is replaced by the **y** axis, etc., as shown in Figure 9.
4. Measure the RF voltages emanating from the EUT as a function of frequency over the desired frequency range. Depending on the measurement device used, either peak, quasi peak, or average measurements may be made. Note that if peak, quasi peak, or average measurements were made for any signal on the previous axis they should be repeated at the same frequency on the second axis to assure that complete data set has been obtained. If new signals are identified on this axis where measurements were not made on the previous axis, the previous axis must be repeated to complete the set of data for the correlation. These measurements are referred to as V_{yzx} versus frequency.
5. Rotate the EUT through two additional successive 90° right hand rotations, such that the **y** axis is replaced by the **z** axis, etc., as shown in Figure 10.

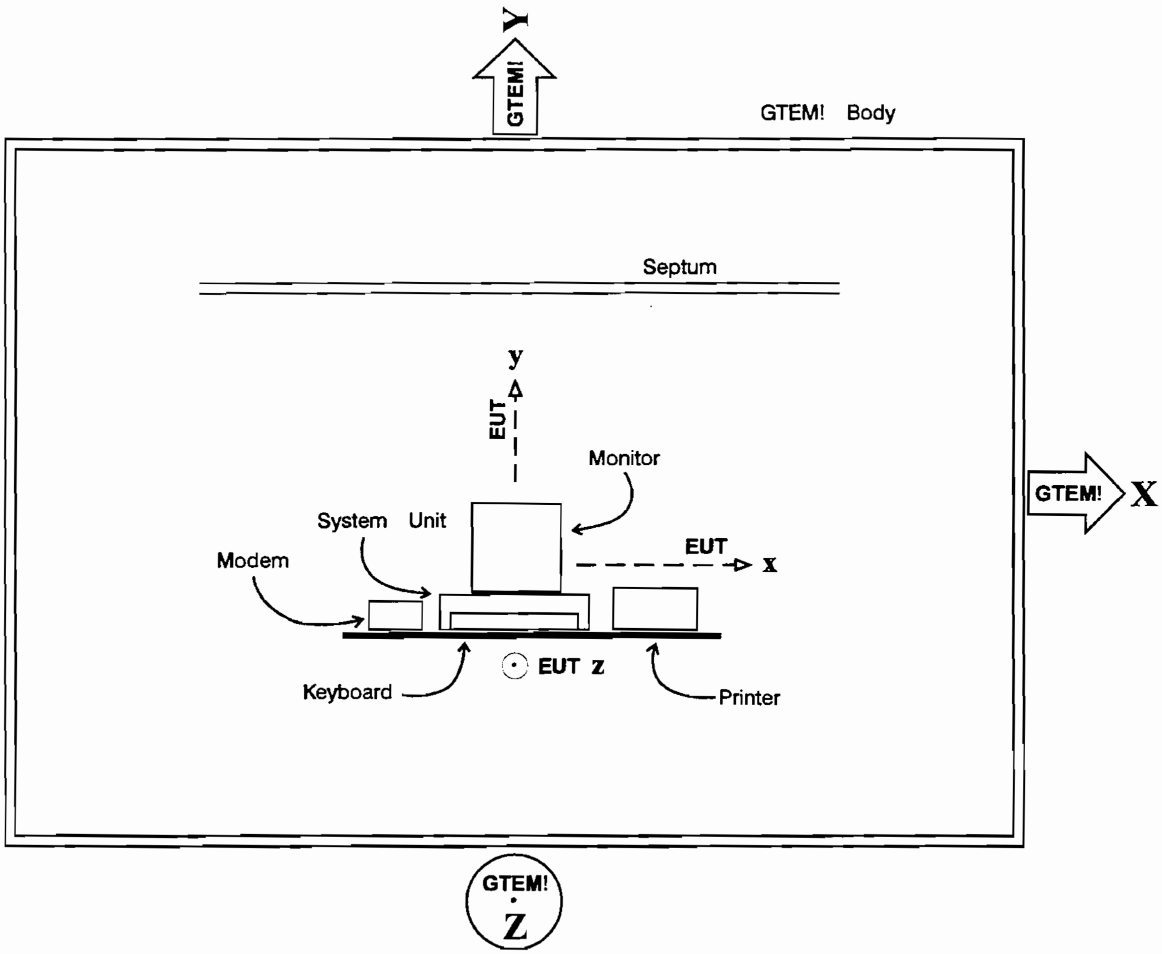

Figure 8. View of typical EUT system installed in large GTEM (as seen from apex) with GTEM (**X**,**Y**,**Z**) and EUT (**x**,**y**,**z**) axes aligned for measurement of V_{xyz}.

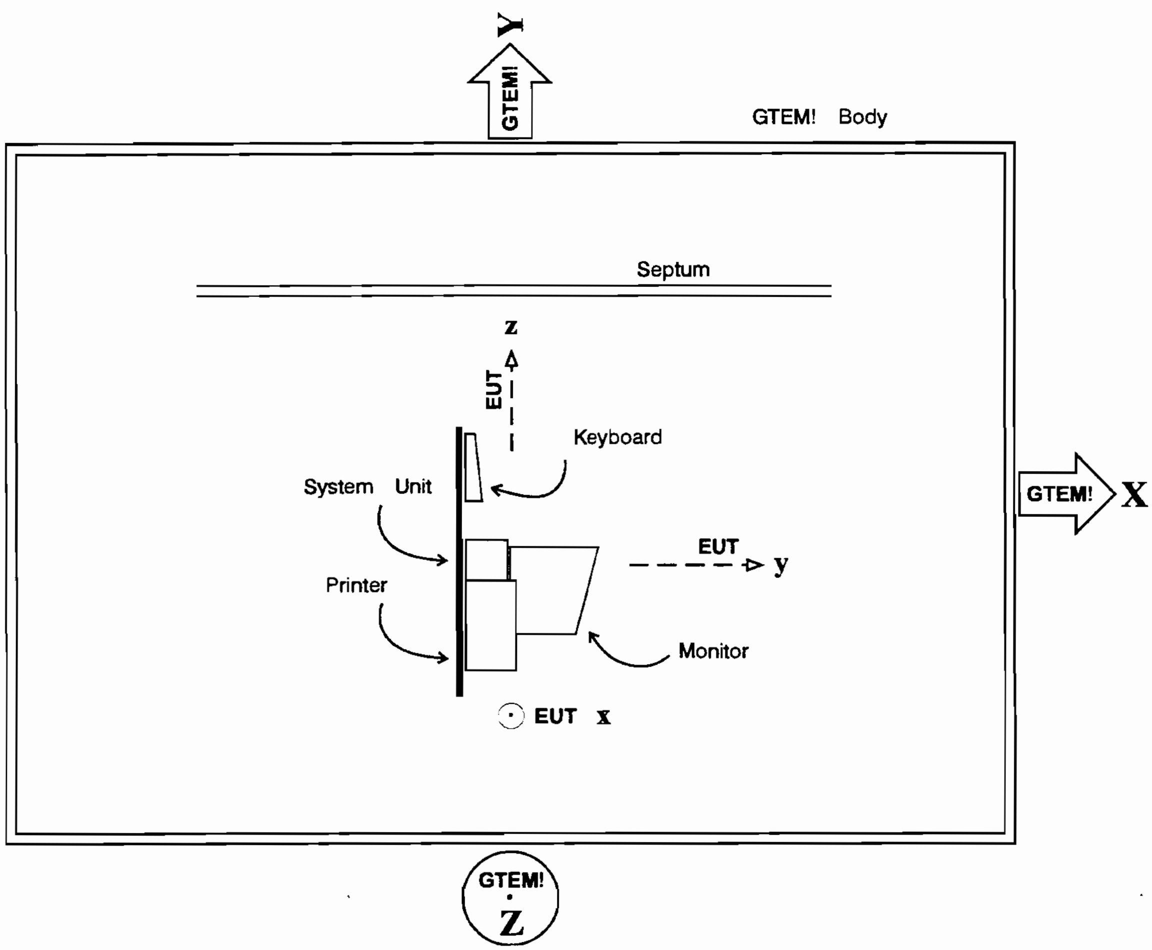

Figure 9. View of typical EUT system installed in large GTEM (as seen from apex) with GTEM (**X**,**Y**,**Z**) and EUT (**x**,**y**,**z**) axes aligned for measurement of V_{yzx}.

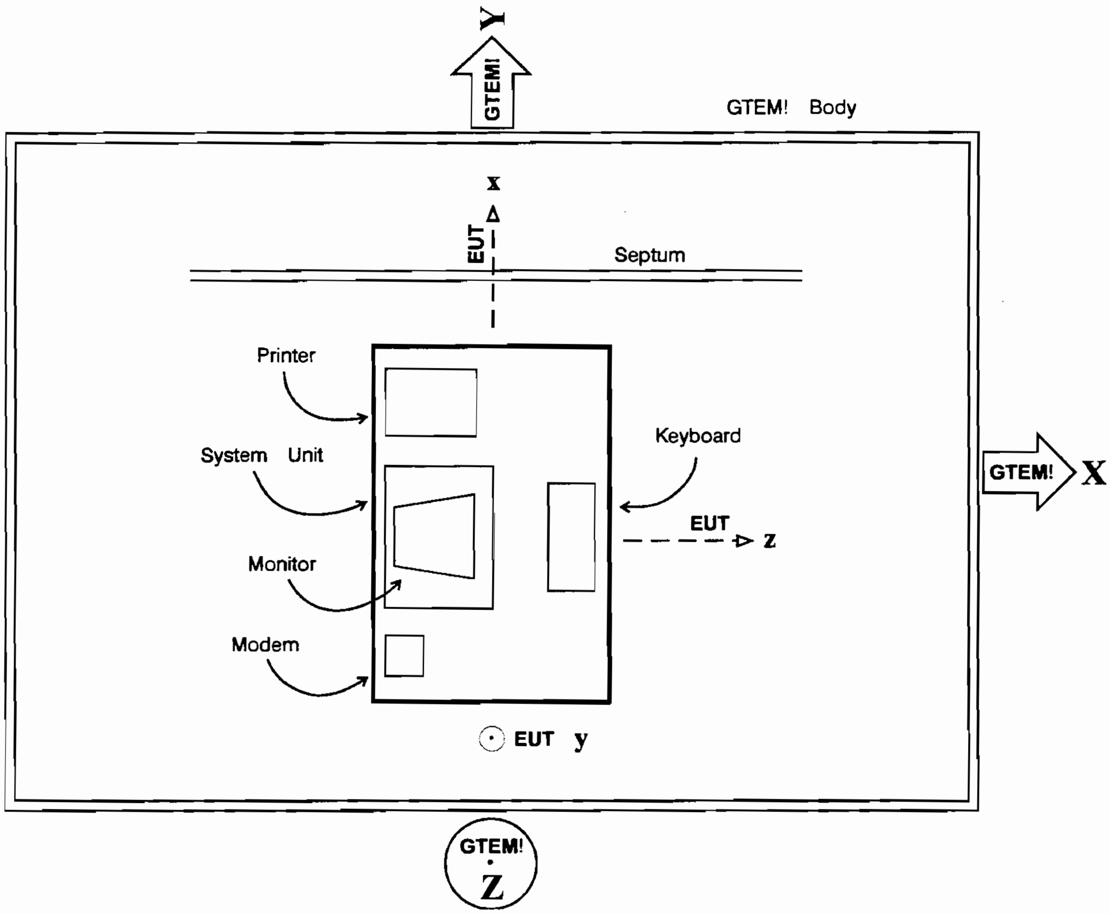

Figure 10. View of typical EUT system installed in large GTEM (as seen from apex) with GTEM (**X**,**Y**,**Z**) and EUT (**x**,**y**,**z**) axes aligned for measurement of V_{zxy}.

6. Measure the RF voltages emanating from the EUT as a function of frequency over the desired frequency range. Depending on the measurement device used, either peak, quasi peak, or average measurements may be made. Note that if peak, quasi peak, or average measurements were made for any signal on the previous two axis they should be repeated at the same frequency on the third axis to assure that a complete data set has been obtained. These measurements are referred to as V_{zxy} vs frequency.

After completion of these measurements, the tester should have a matrix of measurements that consists of a frequency and three associated RF voltage measurements all made with the same detector function. Note that if a signal was found on the second or third axis measurement, that was not found on the first axis measurement, that measurement would have to be repeated on the other axes to assure a complete data set, to ensure that no measurable directional component of the signal was missed. A value for the noise measured at a given frequency where signal components were measured may be necessary to complete the measurement set.

A DOS-based utility program is included with the GTEM that performs the correlation computations for the data taken as described above. This software must be used because the computations are too complex to be performed by hand in a reasonable amount of time.

Software Computations - The correlation algorithm software for the GTEM accomplishes function is described below, given the three voltage versus frequency measurements V_{xyz}, V_{yzx}, and V_{zxy} for three orthogonal orientations of the equipment under test (EUT) in the GTEM.

At each frequency, the three-position correlation algorithm:

- Performs a root sum of the squares summation of the three orthogonal voltages,
- Computes the total power emitted by the EUT as determined from the summation of the three voltages and the TEM mode equations for the GTEM,
- Computes the current excitation of an equivalent tuned, half-wave Hertzian dipole when excited with that input power,
- Computes the field intensity at appropriate height intervals over the total, operator selected scan height, either 1 to 4 metres or 2 to 6 metres for both vertical and horizontal polarizations of the receive antenna when the equivalent tuned resonant dipole is placed at an appropriate height over a perfect ground plane,
- Selects the maximum field strength (larger) value of the horizontal or vertical polarizations,
- Presents this maximum value for comparison to the chosen EMC specification limit.

The GTEM feed connector voltages produced by radiated emissions from the EUT at each of three orthogonal axes are measured, then at each frequency an equivalent set of fixed dipole antennas that would produce the same voltages at the GTEM connector are defined via computer computation. Once these equivalent antennas are defined, the OATS field intensities for comparison to the given specification limit are computed from the set of equivalent dipoles at each frequency, given the separation and geometry of the test setup.

The accuracy of the measurement is of prime importance. A report on the relative accuracy of the GTEM for radiated emissions measurements is given in Annex B: *Radiated Emissions Test Performance of the GHz TEM (GTEM) Cell.*

GTEM MANUAL EUT MANIPULATOR (OPTIONAL)

Introduction

The Mini-Manipulator is designed for use with EMCO Model 5407 GTEM cells to accomplish a variety of EMC tests including those for compliance with the rules and regulations of the Federal Communications Commission (FCC) and the European Union (EU). The use of the GTEM for such testing complies with the intent of §5.4.2 Alternate Test Sites, in ANSI C63.4-1992. The Mini-Manipulator used in the GTEM facilitates rapid testing of an equipment under test (EUT) using not only the standard three-position test procedure, but nine, twelve, twelve-plus-four, and other test procedures that are needed to provide near-field measurements and to characterize special EUTs as well.

EMC measurements in the GTEM require that the EUT be measured in at least three orthogonal positions so that enough data are collected to predict or "correlate" the performance of the EUT to measurements on an open-area test site (OATS) or in a semi-anechoic chamber. Whether measuring the EMI emissions or immunity of an EUT, tests must be made with it in several positions. Positioning the EUT for each measurement can be done manually, but this is quite time consuming and can require two or three people to reposition the EUT inside the GTEM. Not only does changing the EUT position take time, but supplies of low-permittivity dielectric materials are needed to support it in each measurement position. The time to manually position the EUT can be the major part of the total test time when nine or more positions are needed.

Mini-Manipulator Platform Apparatus. The Mini-Manipulator platform apparatus consists of a cradle with EUT turntable (top turntable), and a cradle support frame also with turntable (bottom turntable). Rotation is possible in three axes: the bottom turntable azimuth axis perpendicular to the floor of the GTEM,

the top turntable azimuth axis perpendicular the bottom of the cradle, and the cradle horizontal tilt axis. The Mini-Manipulator for the Model 5407 is shown in Figure 11. The EUT turntable includes holes for anchor points for securing the EUT during testing. The Mini-Manipulator is constructed of low permittivity wood and nonmetallic fasteners to minimize perturbation of the electromagnetic fields. The minimal effect of a manipulator on test results is described in [2].

Mini-Manipulator Operation Theory

Measurements in a GTEM. A GTEM may either receive or transmit; thus electromagnetic interference (EMI) measurements in a GTEM may be of either emissions or immunity. Among emissions measurements are far-field, near-field, and some special measurements. To predict the performance of the EUT during measurements of its emissions on an open-area test site (OATS), its emissions must be measured in a specific set of positions in the GTEM. Predicting EUT performance on an OATS by making measurements in a GTEM is also called "correlation," and the mathematical process is often called the "correlation algorithm."

Simplified Far-Field Measurements may be made of an EUT in a GTEM to predict or correlate its OATS-measured emissions [3, 4]. These measurements are usually made to show compliance to standards, e.g., CISPR 22 or FCC Part 15, in which it is only necessary to know the maximum E-Field versus frequency within a specified range of heights at a certain distance. For example, FCC tests for home computers search heights from one to four metres above the ground at a distance of three meters over the frequency range of 30 MHz to 5 GHz. These simplified measurements require emissions to be measured with the EUT in only three orthogonal positions. This is called the 3-measurement, 3-input correlation algorithm. The main simplifying assumption in this algorithm is that the EUT has gain no greater than a dipole, i.e., a dipole radiation pattern.

Near-Field Measurements may be made of an EUT in a GTEM to correlate its emissions over the frequency range of 9 kHz to 30 MHz [4]. This is called the 9-measurement, 9-input correlation algorithm, and requires measurement of emissions with the EUT in nine positions. The EUT is assumed to be much smaller than a wavelength in its largest dimension; a reasonable assumption below 30 MHz for EUTs that will fit into a GTEM. While this algorithm was originally intended for near-field measurements below 30 MHz, it also works well for far-field measurements above 30 MHz. It is valid from 9 kHz to 5 GHz.

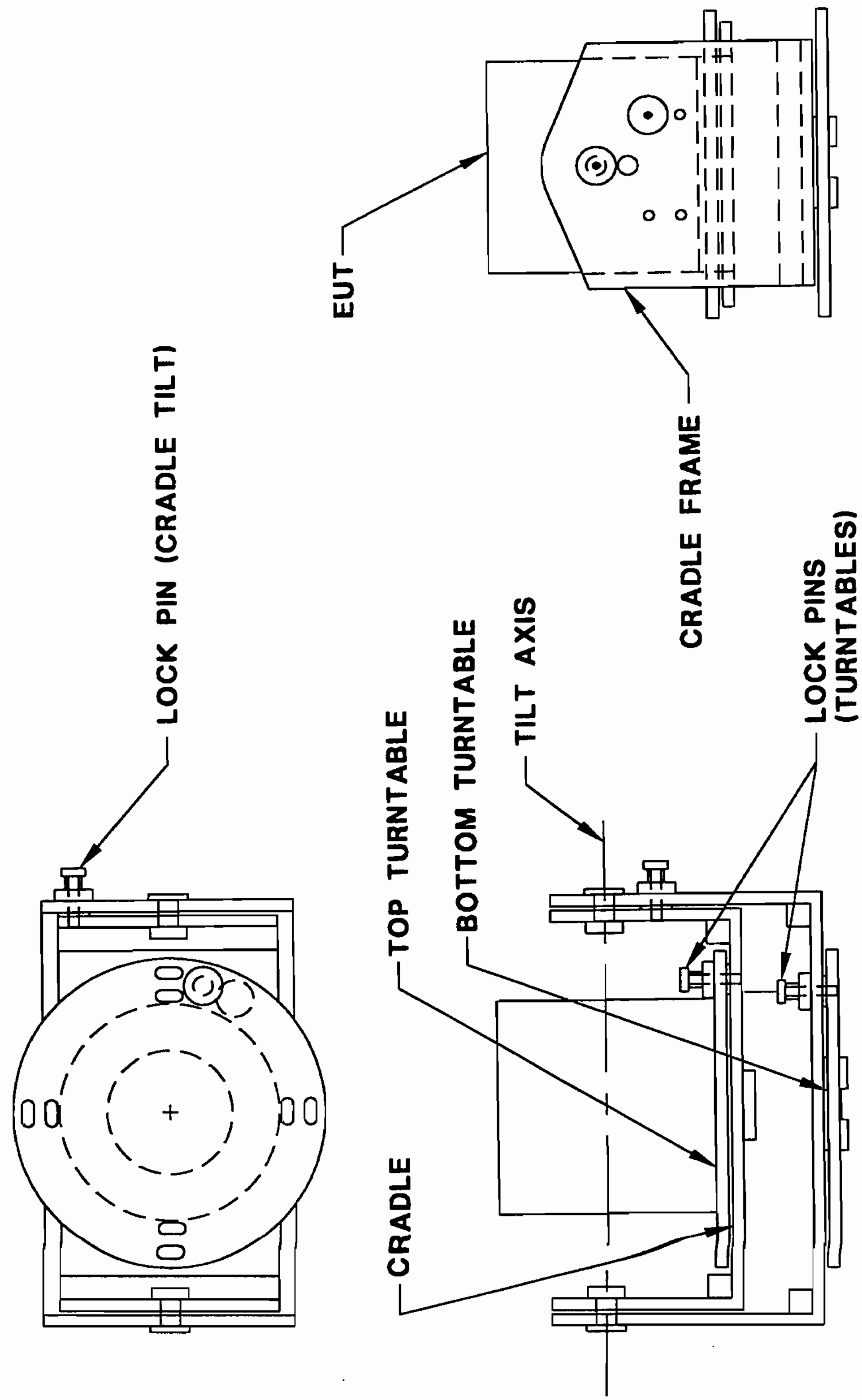

Figure 11. Mini-Manipulator for EMCO GTEM! Model 5407.

Special Measurements are sometimes required because the EUT may have gain greater than a dipole [5, 6], in which case the radiation pattern may be cardioid or other unidirectional. Above about 500 MHz, some EUTs may have an incidental unidirectional pattern because of the way they are constructed, but others have a unidirectional pattern because they are intentional transmitters with a built-in antenna. There are two algorithms which may be used, depending on what one wants to know about the EUT. The simplest one is the 12-measurement, sorted 3-input correlation algorithm, and the other one is the 12+4-position correlation algorithm. In both of these algorithms, the EUT is viewed as a cube and measurements are taken of the emission from each of its faces in both polarizations. The 12-measurement, sorted 3-input correlation is used when it is not necessary to know anything about the shape of the radiation pattern of the EUT. It is often used to test small Telecom Terminal Equipment, such as cellular telephones, up to 10 GHz. It is valid from 30 MHz to at least 10 GHz. The 12+4-position correlation algorithm is used when one needs to estimate the shape of the radiation pattern of the EUT. It is valid from 30 MHz to 5 GHz.

Immunity Measurements may be made in the GTEM to satisfy standards such as MIL-STD-462 or IEC 1000-4-3. If the shape of the radiation (sensitivity) pattern of the EUT is unknown, then its front, back, and both sides must all be exposed to the test signal in both horizontal and vertical polarizations. To do this, eight positions must be tested so that the four usually vertical sides of the EUT are tested in both polarizations facing the apex of the GTEM. If the operator already knows that only one side, e.g., the back, of the EUT is sensitive to external electromagnetic fields, then the testing can be reduced to exposing only its one sensitive side to the apex of the GTEM in both polarizations.

Installing the Mini-Manipulator and EUT - Position the cradle turntable, base turntable, and cradle tilt to the 0° marks. For the Model 5407, place the Mini-Manipulator such the grooves straddle the center seam strip. The suggested start position is with the cradle side plates perpendicular to the center longitudinal seam, and spaced approximately 20 cm from the absorber tips. Place the EUT on the cradle turntable and secure it with nonmetallic cords or rope. Polystyrene blocks may be placed under the EUT for elevation before securing.

Naming the EUT Faces. For the purposes of this discussion, consider the EUT as a cube. Figure 12 shows a three-dimensional Cartesian coordinate system with a cube centered on it. The face from which a positive axis emerges is named for that axis, i.e., "+X" is the face of the cube from which the positive X-axis emerges. Name the front of the EUT "−Z" and the back "+Z". Looking at the "+Z" face (the back), name the right-hand side "+X" and the left-hand side "−X". Name the top "+Y" and the bottom "−Y".

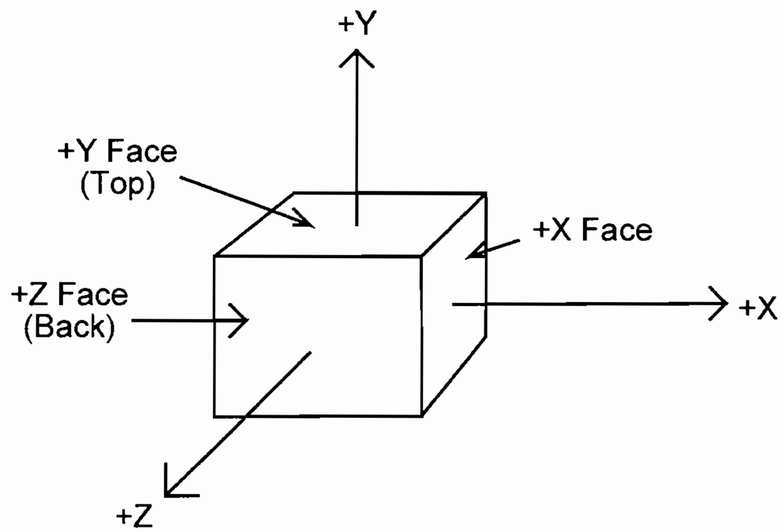

Figure 12. EUT as a cube on Cartesian axes showing names of faces.

This is the coordinate system for the EUT. Note that the three orthogonal positions of the EUT exchange the EUT coordinates relative to the GTEM coordinates. The first position is identified as XYZ, the second as YZX, and the third as ZXY; and the voltages measured at the apex of the GTEM in the three positions are called V_{XYZ}, V_{YZX}, and V_{ZXY}.

EUT Positions. Emissions tests all require sets of positions which are built on the basic three orthogonal positions needed by the 3-measurement, 3-input correlation. Immunity tests require positions based on the test standard; these are not necessarily extensions of the basic set of three orthogonal positions.

Sets of Positions Needed. For the 3-measurement, 3-input correlation, any set of three orthogonal positions can be used. A typical rotation series is as follows.

For a Model 5407 with the door on the right-hand side as looking from the apex, position the manipulator with the 0° mark pointing towards the right side of the door. Secure the EUT to the top turntable. Figure 13a shows a schematic of this arrangement as seen looking in the door. This is the first test position used to measure V_{XYZ}. Next release the cradle tilt lock pin and swing the cradle away from the door to the 90° tilt position. Note the EUT X-axis now points down, as shown in Figure 13b. Now rotate the top (EUT) turntable to 90°, as shown in Figure 13c, and measure V_{YZX}. Finally, rotate the top turntable to the 180° position (Figure 13d), and the bottom turntable to 90° (Figure 13e), and measure V_{ZXY}.

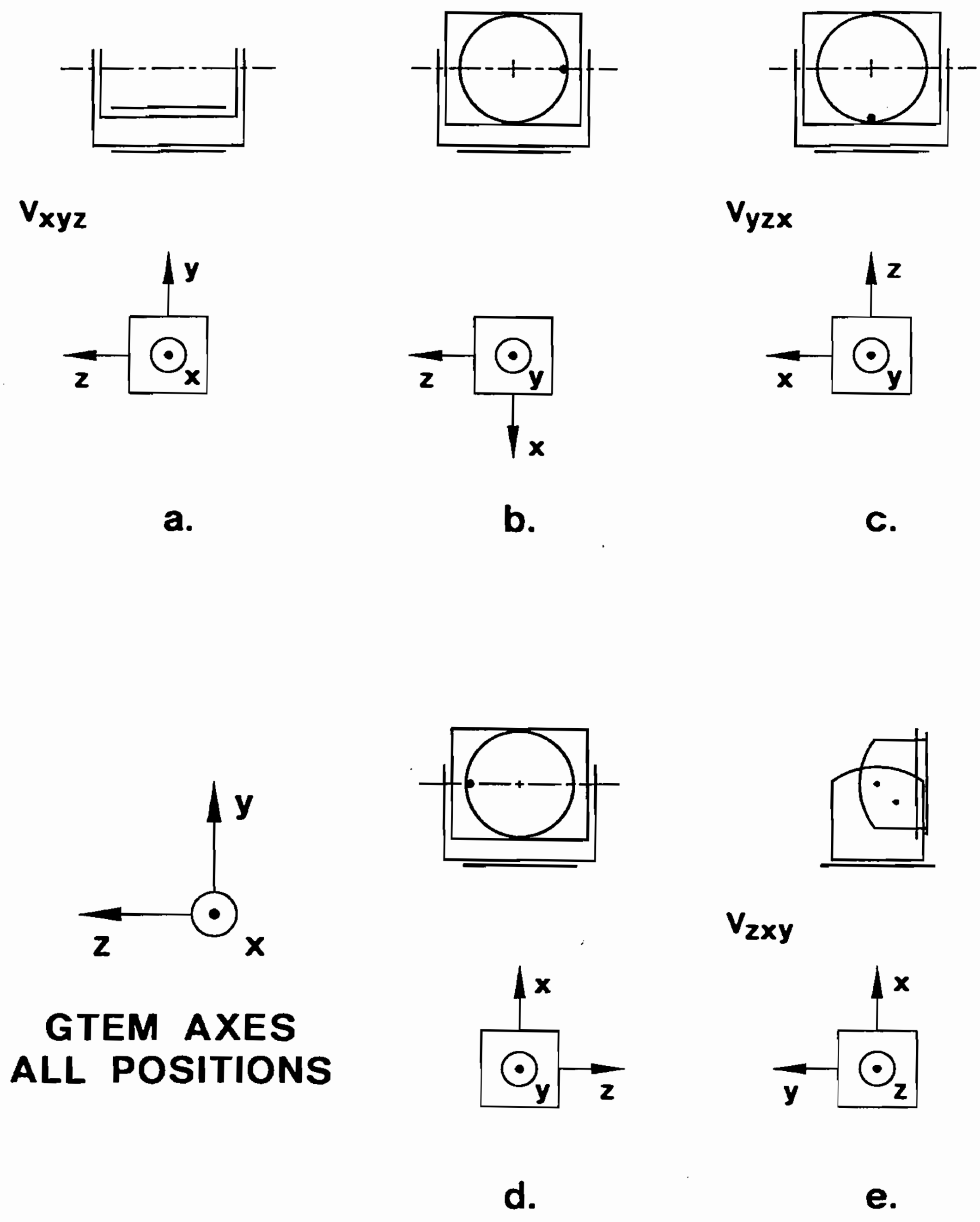

Figure 13. Mini-Manipulator positions for 3-position emissions test in an EMCO GTEM! Model 5407.

For the 9-measurement, 9-input correlation, at each of the measurement positions shown in Figures x, x, and x, rotate the bottom turntable ±45° and take additional voltage readings. For the 12-measurement, sorted 3-input correlation, and for the 12+4 position correlation, contact the factory for the suggested Mini-Manipulator positioning. The 12-measurement, sorted 3-input correlation eliminates the assumption of gain no greater than a dipole, and can be used to do tests in which the EUT is replaced by a dipole on the OATS and the limit levels are in terms of the power at the dipole terminals needed to produce the same emission level measured from the EUT. The 12+4 position correlation estimates the directivity, and thus the gain, of the EUT, then uses this estimated gain in the 3-measurement, 3-input correlation. These correlations are discussed in more detail in [5, 6].

MAINTENANCE

Periodic maintenance will assure the continued performance of the GTEM There are several areas to be considered.

Periodic Performance Monitoring

On-site VSWR measurements are normally performed at the conclusion of installation procedures for the Model 5407. They are also performed at the factory for all GTEMs. A satisfactory VSWR measurement is necessary before any GTEM can be shipped. Determination of continued performance to specified parameters may be assured by periodic remeasurement of the VSWR. Periodic VSWR measurement will detect any change in performance parameters that would signal unacceptable performance. The VSWR measurement should be performed on a schedule as recommended by the customer's Quality Engineering. The default time period between such evaluations (this is not a calibration) would be six months.

Periodic Owner / Operator Maintenance Items

Finger Stock - There is a large amount of finger stock used in the construction of the GTEM Some of this finger stock is accessible in the normal course of GTEM operation. Periodic visual inspections should be made to determine if there is need to clean the finger stock or if damaged replace it. Replacement finger stock for the doors is available from the factory (PN:890XXX). Replacement finger stock for the connector panels and the load board access panels is also available (PN:890258). Finger Stock may be cleaned by using an aerosol lubricant such as WD-40 to loosen the debris and then low pressure air or another aerosol to remove excess lubricant.

CAUTION:	Working with finger stock in cleaning should be done with care. There are numerous sharp edges on the finger stock material and a cautious approach is needed to assure safe completion of the task.

Air Vents - The air vents on the Model 5407 GTEM should be checked to be sure that there is free airflow to assure optimum cooling. A small soft brush may be used to clean the honeycomb.

Floor Panels - The connector feed through panels in the floor of the GTEMs will attract small particles of dirt or other debris. Inspection of their continuity on a periodic basis is necessary to assure continued shielding. To inspect for an accumulation of dirt, the panels should be removed and the opening and the flange should be inspected and any accumulated dirt or debris removed. The finger stock should be inspected at this time, and cleanse or replaced if required (PN 890258).

Connectors - The RF and other connectors are somewhat delicate in their floor mounted position. Periodic examination of these connectors for damage should prevent use of a connector with damaged pins or other connections, assuring proper operation of the connectors. During use, care should be taken to protect these connectors if they are not in use.

Absorber Tips - The RF absorber tips are fragile and are easily broken off. They may be easily replaced with almost any contact cement or with rapid curing epoxy cement. If the tips are too damaged to reuse, they may be replaced by cutting off the entire tip at a point where the absorber body is about 10 cm by 10 cm and replacing the entire tip. Extra absorbers are available from the factory. Absorber tip protectors are installed on some GTEMs where personnel access inside a GTEM is expected. These tip protectors are cut from block expanded polystyrene. They will protect the tips from casual contact. Extra or replacement tip protectors are available from the factory (PN 870071).

Shielded Viewing Windows - The shielded viewing windows (if the GTEM is so equipped) are fabricated from an acrylic plastic material. Cleaning may be accomplished with a plastic cleaner such as Novus Plastic polish.

CAUTION!	Do not use petroleum products, abrasives or solvents for cleaning window, as damage to the acrylic material could result.

GTEM Cleaning - Overall cleaning of the GTEM inner and outer surfaces may be accomplished by the use of standard non-abrasive cleaners. Periodic cleaning of the interior with a vacuum cleaner will reduce the possibility of debris build-up in the connector panel area.

CAUTION!	Care in cleaning in the vicinity of the RF absorbers will preclude damage to their tips.

Load Boards - Load Boards should not require periodic maintenance other than periodic inspection and cleaning of contact surfaces, to prevent the occurrence of any film or corrosion. Any foreign substance that is found on the boards or connector surfaces should be removed

Other Maintenance - Other maintenance on the GTEM is not required. Factory engineering personnel should be consulted in the event of damage or failure to operate properly after maintenance procedures.

No Scheduled Factory Maintenance Required - **There is no scheduled factory maintenance required.**

In Case of Damage - **If severe damage occurs to a GTEM, please contact the factory for guidance. Please have ready a description of the nature and scope of the damage.**

GTEM Options

There are many optional features for a device such as the GTEM This section describes those that can be obtained and installed by the purchaser. Additional options are available as factory-installed equipment. The options discussed in this section are available for customer installation. Please contact the factory for details.

Standard Options

Additional Blank Feed Thru Panel - Additional 304 mm square blank, removable panels (PN: 15346) are available to replace any panels furnished with the unit to accommodate additional cable entries to the GTEM. These are interchangeable with the panels furnished with the GTEM

Internal EUT Manipulator - A multi-position EUT manipulator is available for the GTEM to assist in locating the EUT for radiated emissions testing.

Custom Signal Filters - For customers with unique signal input and output requirements, custom designed filters are available mounted to penetration panels.

Custom Power Filters - For additional EUT power input requirements, a number of single and three phase input power filters are available to provide

almost any input power requirement to EUT in a GTEM These power inputs are independently switched, *i.e.*, they are not controlled via the main power switch on the Power Distribution Panels.

Non-Standard Options

It is recognized that every application for a GTEM in EMC testing will be unique, or may have unique requirements. If there is a modification to the GTEM that will accelerate test performance, contact the factory. Most of the standard options listed above are field installable and can retrofitted after delivery.

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WARRANTY

EMC Test Systems, L. P. warrants that our GTEM will be free of defects in materials and workmanship from a period of two years from the date of first use following installation and acceptance. If you notify us of a defect within the warranty period, we will, at our option, either repair or replace the defective portion.

There will be no charge for warranty services performed at the location we designate. You must, however, prepay inbound shipping costs and any duties or taxes. We will pay outbound shipping costs for a carrier of our choice, exclusive of any duties or taxes. You may request warranty services to be performed at your location, but it is our option to do so. If we determine that warranty service can only be performed at your location, you will not be charged for our travel related costs.

This warranty does not apply to;

1. Normal wear and tear of materials.
2. Consumable items such as fuses, resistors, lights, etc.
3. Anechoic and finger stock material (limited to the warranty supplied by the original manufacturer).
4. Software (warranted separately).
5. Damage caused by improper use and maintenance.
6. Operation outside of specifications.
7. Modification without written authorization.

THIS WARRANTY IS EXCLUSIVE. NO OTHER WARRANTY, WRITTEN OR ORAL, IS EXPRESSED OR IMPLIED, INCLUDING BUT NOT LIMITED TO, THE IMPLIED WARRANTY OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE.

THE REMEDIES PROVIDED BY THIS WARRANTY ARE YOUR SOLE AND EXCLUSIVE REMEDIES. IN NO EVENT ARE WE LIABLE FOR ANY DAMAGES WHATSOEVER, INCLUDING BUT NOT LIMITED TO DIRECT, INDIRECT, SPECIAL, INCIDENTAL, OR CONSEQUENTIAL DAMAGES WHETHER BASED ON CONTRACT, TORT, OR OTHER LEGAL THEORY.

Please contact our offices regarding any questions you may have regarding use and maintenance.

Please contact our offices, Sales Department, for a Return Material Authorization Number before shipping equipment for repair. Failure to do so will cause delay.

ANNEX A

Theory of GTEM Correlations

Emission measurements in TEM cells and TEM lines

A.1 Multipole model

Any finite sized radiation source may be replaced by an equivalent multipole expansion which gives the same radiation pattern outside some volume bounding the source. If the source is electrically small, then the initial multipole moments, electric and magnetic dipoles, will yield an accurate representation. The above holds for an arbitrary source. If the source itself consists of electric and magnetic dipole like elements only, then the electrically small restriction may be relaxed.

The basic approach of TEM cell or TEM line to open area test site correlation routines is to use a set TEM cell measurements to determine the multipole moments. Once the multipole moments are known, radiation either in free space or over an infinite ground plane may be simulated numerically. In this fashion it is possible to simulate the various source to receiver antenna configurations required by OATS emission standards.

For two-port TEM cells or TEM lines, measurements at both ports yield both amplitude and relative phase information [A1-A5]. In this manner both the magnitude and phase of the multipole moments may be determined and the radiation pattern accurately simulated, including possible nulls due to phase cancellation. For one- port TEM cells or TEM lines no relative phase information is available; thus, it is only possible to determine the magnitudes of the multipole moments [A6-A8]. Such a representation still well-simulates emission maximums [A9-A10] which are of primary interest in EMC measurements; however, radiation pattern nulls may not be well-simulated.

A.2 Two-port TEM cell or TEM line correlation routine

See references [A1-A5].

A.3 One-port TEM cell correlation routine

The most time-efficient one-port correlation routine is based on the assumption that the EUT may be reasonably represented by its initial multipole moments, namely the electric and magnetic dipole moments. Three voltage measurements are then made in a TEM cell from which the EUT total radiated power may be calculated. The individual dipole moments are not separately determined. The total radiated power is then used to simulate the maximum EUT fields over a ground plane based on a model of parallel dipoles, either horizontal or vertical, radiating the same total power.

A.3.1 TEM cell voltage measurements: 3-positions

The EUT emissions are measured in three positions which are determined as follows. Assign an axis system (x,y,z) to the TEM cell and to the EUT. A standard choice is to align the z-axis in the direction of propagation, the y-axis with the E-field (vertical) and

the x-axis with the H-field. A local coordinate "primed" system (x',y',z') is assigned to the EUT. Position 1 aligns x' with x, y' with y, and z' with z. Position 2 is obtained by simply permuting the primed EUT axes; x' with y, y' with z, and z' with x. This is equivalent to two 90 degree rotations of the EUT. Position 3 is obtained by further permutation: x' with z, y' with x, z' with y. Denoting the three voltage measurements by V_{p1} - V_{p3} (dBμV) it may be shown that the total radiated power P_0 due to the EUT is then given by the equation

$$P_0 = \frac{40k_0^2}{e_0^2 Z_c}\left(10^{\frac{V_{p1}-120}{20}} + 10^{\frac{V_{p2}-120}{20}} + 10^{\frac{V_{p3}-120}{20}}\right) \quad \text{(W)}, \tag{A1}$$

where k_0 is the wave number $(2\pi/\lambda)$, and Z_c is the characteristic impedance (typically 50 Ω). The factor e_0 is a normalization factor related to EUT location (x,y) in the TEM cell cross section and the cross-sectional geometry, approximated analytically by the equation

$$e_0 = \frac{2}{a}\sqrt{Z_c}\sum_{m=1,3,5...}\left(\frac{\cosh My}{\sinh Mb}\right)\cos Mx \sin Ma J_0(Mg) \quad (\Omega^{1/2}/\text{m}), \tag{A2}$$

where $M = m\pi/2a$, $2a$ is the TEM cell width at the EUT location, g is the gap width between the septum and side wall, and J_0 is the zero-order Bessel function. Alternately, e_0 can be determined experimentally via a field measurement of E (cell empty) at the EUT location (x,y) with a known input power P_i and the equation

$$e_0 = \frac{E(x,y)}{\sqrt{P_i}} \quad (\Omega^{1/2}/\text{m}). \tag{A3}$$

EUT emissions over a ground screen are simulated by assuming the same total radiated power is emitted by a short dipole (replacing the EUT). The equations for the fields from a dipole are well known and the ground screen may be accounted for by introducing an image dipole. The fields may be calculated over the equivalent sweep path of receiving antenna if required and the maximum determined for both polarizations. The maximum for the two polarizations would then give the maximum possible field. The geometry factor due to sweeping the observation point is designated as f_{max}, and the maximum field E_{max} is given by the equation

$$E_{max} = \left(\frac{3}{4}\frac{\eta_0}{\pi}P_0\right)^{\frac{1}{2}} f_{max}, \tag{A4}$$

where $\eta_0 = 120\pi$ Ω is the free space wave impedance. The factor f_{max} is given by the equation

$$
f_{\max} = \begin{cases} \left| \dfrac{e^{-jk_0 r_1}}{r_1} - \dfrac{e^{-jk_0 r_2}}{r_2} \right|_{\max} & \text{horizontal polarization} \\ \left| \dfrac{s^2}{r_1^2} \dfrac{e^{-jk_0 r_1}}{r_1} + \dfrac{s^2}{r_2^2} \dfrac{e^{-jk_0 r_2}}{r_2} \right|_{\max} & \text{vertical polarization} \end{cases} , \tag{A5}
$$

and s is the OATS separation distance. The distances r_1 and r_2 between the EUT and its image to the receive point are given by the equations

$$
\begin{aligned} r_1 &= \left[s^2 + \left(R_H - h \right)^2 \right]^{\frac{1}{2}} \text{ m}, \\ r_2 &= \left[s^2 + \left(R_H + h \right)^2 \right]^{\frac{1}{2}} \text{ m}, \end{aligned} \tag{A6}
$$

where R_H and h are the receive antenna and EUT heights respectively over the ground plane. Typically R_H is varied between 1 and 4 meters. For correlations to free-space, omit the r_2 terms in Eqn. A5. The above equations are readily programmed. Alternately $E_{\max}$ may be expressed in dBμV/m as

$$
E_{\max} = 10\log(P_0) + 20\log(f_{\max}) + 139.5 \quad (\text{dB}\mu\text{V/m}) \tag{A7}
$$

The factor $20\log(f_{\max})$ may be calculated, or interpolated from precalculated tables for standard geometries.

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ANNEX B

Radiated Emissions Test Performance of the GHz TEM (GTEM) Cell

RADIATED EMISSIONS TEST PERFORMANCE

OF THE GHz TEM CELL

Abstract

The GHz TEM (GTEM!) Cell has recently been recognized as a competing technology for the accomplishment of electromagnetic compatibility (EMC) radiated emissions testing for the demonstration of compliance with commercial specifications. As a competing technology, the direct comparison of the performance of a GTEM!, for such compliance measurements, to the results obtained from an Open Area Test Site (OATS), are an obvious and necessary step. This paper describes the direct comparison of results of two series of tests. Two differing comparisons are described; three separate sets of reference dipole comparison measurements, and two full Personal Computer systems tested per the requirements of ANSI 63.4, Draft 11.4 [1] on an OATS and in a GTEM! In addition to a direct comparison, the resultant data has also been subjected to statistical analysis. The statistical analysis was performed on maximum electric field strength data comparing GTEM! calculated levels with open area test site (OATS) measured levels. Pearson's correlation coefficient and Student's-t distribution were used to analyze the data. Good agreement of results, both by direct comparison and by the statistical analysis have been found, and are described.

Introduction

The GHz Transverse Electromagnetic (GTEM!) Cell, Figure 1, has existed in conceptual form, and as a practical device, for some time [2]. Only recently has the use of this device, as an alternative to radiated emissions measurements on an OATS, been seen as a practical choice [3], [4]. This change has been brought about by additional developments in the theory of this device, such that a direct comparison can be made to the results obtained from an OATS. The main contribution that has brought forward the GTEM! as a practical radiated emissions device has been in the theoretical development of a mathematical model allowing the direct comparison of data taken in a GTEM! to data acquired on an OATS. The software implementation for the GTEM! accomplishes the following, given three voltage versus frequency measurements V_{xyz}, V_{yzx} and V_{zxy} for three orthogonal orientations of the equipment under test (EUT) in the GTEM!

At each frequency:

Performs a vector summation of the three orthogonal voltages

Computes the total power emitted by the EUT as determined from the summation if the three voltages and the TEM mode equations for the GTEM!,

Computes the current excitation of an equivalent tuned, resonant dipole when excited with that input power,

Computes the field intensity at appropriate height intervals over the total scan height, either 1 to 4 metres or 2 to 6 metres for both vertical and horizontal polarizations of the receive antenna when the equivalent tuned resonant dipole is placed at an appropriate height over a perfect ground plane,

Selects the maximum field strength (larger) value of the horizontal or vertical polarizations,

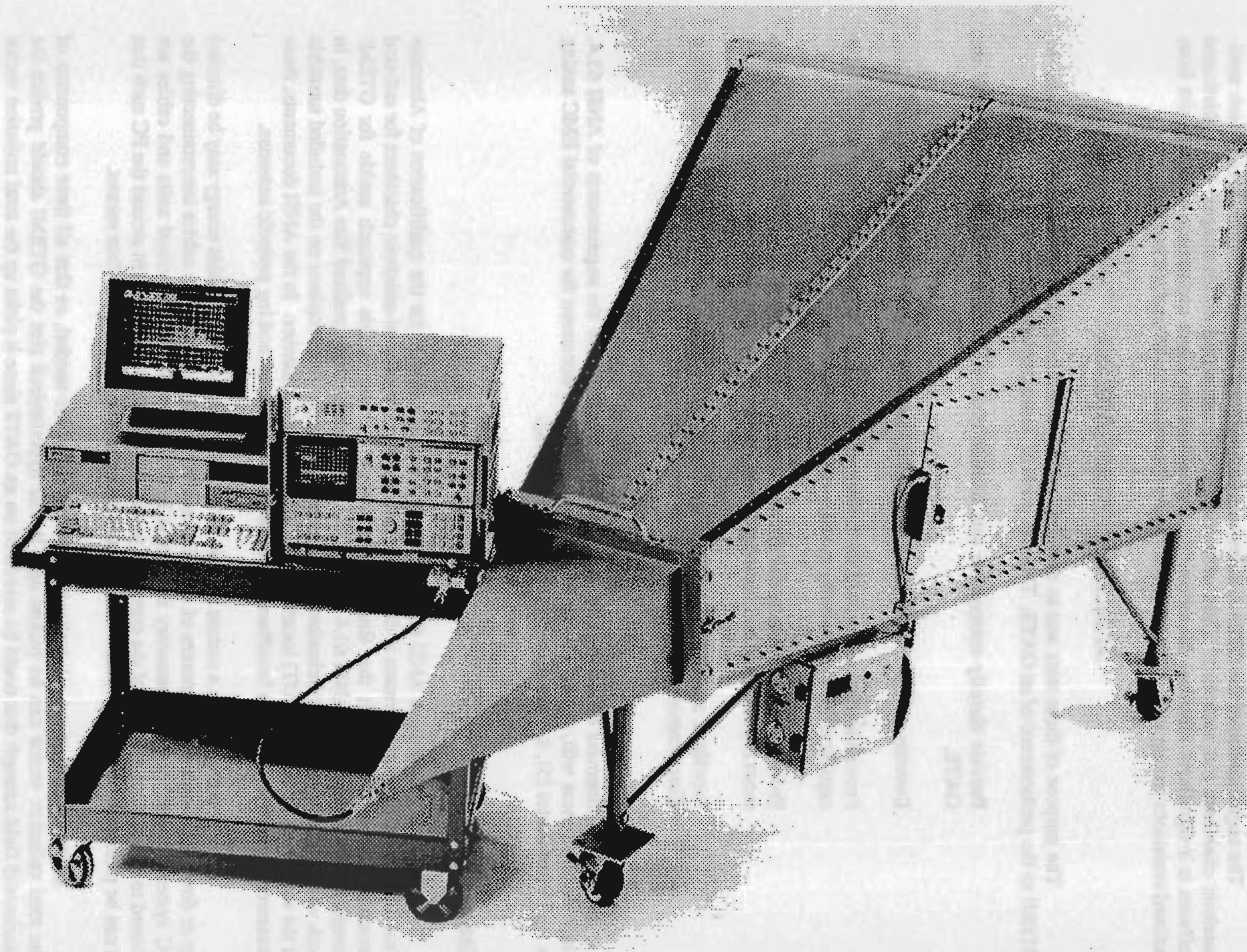

Figure 1. GTEM! Model 5305 with Radiated Emissions testing equipment.

Presents this maximum value as compared to the chosen EMC specification limit.

The augmentation of the GTEM!, a device which presents many of the advantages of both semi-anechoic chambers and traditional TEM cells without accompanying disadvantages, by sophisticated software is a significant technical advancement. This allows the direct comparison of test results from radiated emissions testing in the GTEM! to test results from more traditional test methods

Goals of Testing and Analysis

The purpose of these tests was to develop a valid, direct comparison of the performance of the GTEM! to the performance of an OATS. Thus the goals of testing were:

Provide directly comparable sets of high quality test data from the GTEM! and the OATS.

Develop a simple, direct comparison of the results of these diverse tests.

Provide analytical result of the difference in the GTEM! and OATS performance that is capable of being succinctly stated, yet remains complete.

Provide a supplement to the direct comparison by a statistical analysis that provides a more sophisticated and meaningful comparison of the measurements.

Provide a statistical measure of quality of the compared measurements other than a direct statement of difference of the measurements.

Design of Testing

The development of the specific test approaches was based on the requirements of ANSI 63.4. Since this document will, in time, become the test requirements document for commercial EMC testing in the United States [5], it was selected as the basis for testing.

General

There is provision in ANSI 63.4, for the development of data for the qualification of Alternate Test Sites. While this requirement is directed to the qualification of semi-anechoic chambers for radiated emissions testing, it was felt that there were technical features in this approach usable for GTEM! comparison measurements. ANSI 63.4 requires the development of Normalized Site Attenuation data, in both vertical and horizontal polarizations, from a number of specified locations on the included turntable at the equipment under test (EUT) location in the semi-anechoic chamber. In the ANSI documents, these measurements are made with a broadband antennas such as biconical and log periodic antennas.

A test object produces a certain amount of radiated energy. Some of this energy may be directed up or down depending on the sources of radiation and the coupling among the cables interconnecting the PC system components. In customary traditional EMI tests on OATS, individual units and cables are moved to try to cause as much of the energy as possible to be radiated at a height around the PC such that it can be picked up in the height scan of the measurement antenna, e.g., one to four metres.

In the GTEM!, three orientations of the test object are needed, so that all three components of the total radiation vector can be picked up. It was hypothesized that the GTEM! should predict the maximized field strength that could be measured on an OATS since it picks up the total radiation vector from the test object.

In order to accommodate the size of the planned EUT's, a GTEM! Model 5317 was used. The external dimensions of this device are given in Figure 2.

Reference Dipole Antenna Testing

Equivalence testing for the GTEM! was planned using tunable dipole antennas, The tunable antennas can remain comparatively small over the majority of the frequency range of interest, and dipole antennas are the reference antennas constructed as described in ANSI 63.5 [6], preferred for the resolution of conflicting measurements. The dipoles can be easily placed in the center of the test volume and three orthogonal measurements made to satisfy the requirements for GTEM! testing. They are also easily transferred to the OATS for the comparison testing. When the dipole antennas begin to become large with respect to the size of the GTEM! test volume, they were used as short dipoles with the dipole elements set to a fixed frequency compatible with the size of the test volume.

The resonant dipoles were installed on an OATS with the feed point of the dipole directly over the center of the turntable, The dipole was driven at many frequencies, as appropriate, to 1000 MHz. The test procedure of ANSI 63.4, was used. This procedure requires that the measurement be made at the maximum of the emanation at each frequency. This in turn requires searching the receive antenna in height, and rotation of the turntable to establish the maximum value of the emanation. Measured values were corrected to field strength values by adding cable loss and antenna factors.

The resonant dipoles were then transferred to the test volume of the GTEM! Voltage measurements were made in three orthogonal orientations, and the test control software was used to process the three orthogonal measurements into field strength versus frequency data. These values are directly comparable to those taken at the OATS.

Personal Computer Testing

The second test series involved comparison testing of two different small, desk top Personal Computer systems. They were installed secured to a piece of plywood with the subsystem components and interconnecting cables strapped to the plywood with nylon strapping. The strapping was firm since the entire EUT installation would be rotated to allow three orthogonal axes voltage measurements. Each personal computer system consisted of a system unit, monitor, keyboard, parallel device (printer), mouse and a serial device (printer or modem). These items were installed as shown the figures distributed in ANSI 63.4. These figures require the installation of the EUT on a 1 x 1.5 metre table. In the testing described in this paper a 1 x 1.5 metre piece of 12 mm plywood was used. The system unit was installed with the back edge of the chassis aligned with the back edge of the plywood base and centered. The monitor was centered on the system unit. The printer (required parallel peripheral) was installed to the right of the system unit at a distance of 10 cm. The modem (required serial peripheral) was installed 10 cm to the left of the system unit. The back edges of all of these units were aligned with the back edge of the plywood. The keyboard was centered and aligned with the front edge of the plywood. The mouse was installed 10 cm from the right edge of the keyboard and aligned with the back of the keyboard. All items were secured to the plywood. The plywood array was then transferred into the test volume of the GTEM! used for this testing.

The three orthogonal measurement alignments are shown in Figure 3, showing the orientation for V_{xyz} testing, Figure 4, showing the orientation for V_{yzx} testing and Figure 5, showing the orientation for V_{zxy} testing. The relative position of the subsystem components are shown in these figures. Also shown in the Figures are the calculated field uniformity contours for • 1 dB, • 2 dB, •3 dB and • 4 dB field uniformity referenced to the center of the test volume. Figures 3, 4 and 5 are oriented for the view to be from the apex of the GTEM! cell. To maximize the measured emission values, the draping of the

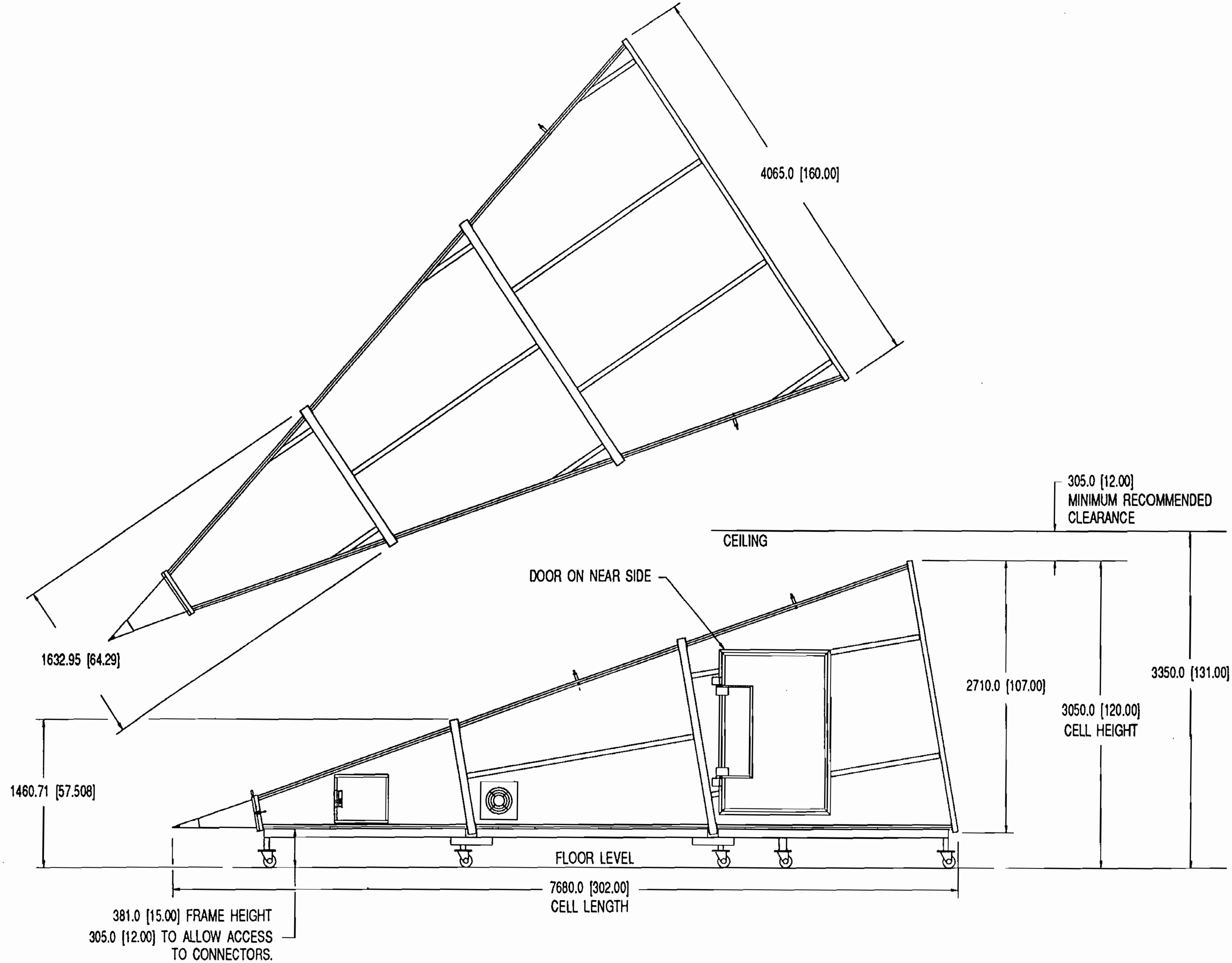

Figure 2. Dimensions of Model 5317 GTEM!

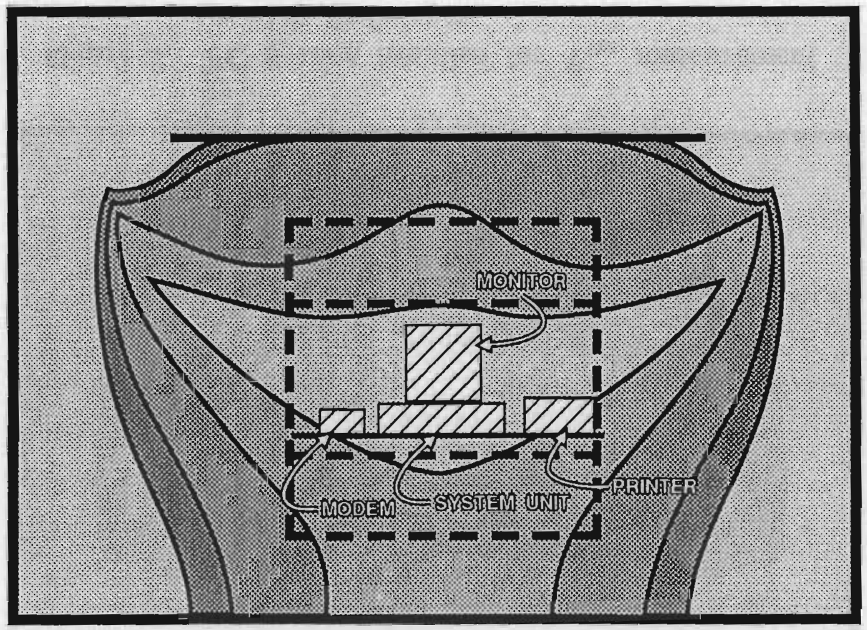

Figure 3. PC System installed for V_{XYZ} measurement as seen from apex.

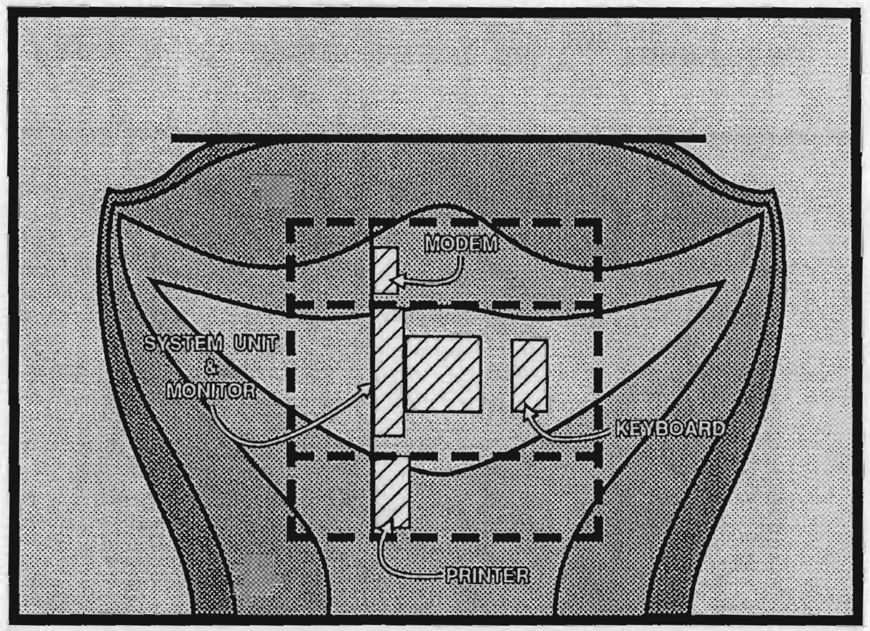

Figure 4. **PC System installed for V_{YZX} measurement as seen from apex.**

cable from the first position measured was preserved for a minimum of 30 cm from the back edge of the table.

After testing in a GTEM! the plywood sheet with the EUT's secured to the sheet was transferred to the OATS for comparison testing. The five highest frequencies detected in the GTEM!, from each PC array, were evaluated at the OATS using the procedures of ANSI 63.4.

Design of Data Analysis

The consideration of how to compare the data between the two types of test facilities, the GTEM! and an OATS is less straightforward than may seem. Two types of analysis of the comparative data were performed, direct and statistical comparisons.

Direct Comparisons

The first comparison of the data is the direct subtraction of the OATS measurement of a signal at any frequency from the GTEM! measurement at the same frequency. This gives a quantitative analysis of the direct difference of the measurements. By subtracting the OATS reading from the GTEM! reading, a positive value indicated that the GTEM! measured signal is larger than the OATS measured signal. Conversely, a negative value indicates that the GTEM! is measuring the emanation lower than the OATS.

The second direct comparison of the data is the determination of the mean and standard deviation of the differences for all data points in a single data set. An upper bound of the difference of the GTEM! and OATS measurements may be set statistically from the standard deviation data.

Statistical Comparisons

Pearson's Correlation Coefficient - Pearson's correlation coefficient [7] and linear regression equation coefficients [8] were calculated for data (the first three sets of dipole data and the first two sets of PC data) in which values from different distances were combined for overall evaluation. The correlation helps to show when the data are not independent and can properly be combined for further analysis.

Meaning of the Value of Pearson's Correlation Coefficient - Values of Pearson's correlation coefficient between +0.6 and +1, and regression line slopes between +0.5 and +1.5 indicate a strong relationship between the samples of data.

Student's-t Statistic - Student's-t statistic for paired, sample variables was used to analyze the comparison data for both the dipoles and the PCs. This approach allowed testing the null hypothesis for the difference between the GTEM! data and the OATS data.

Meaning of Student's-t Statistic. The interval of Student's-t distribution between -t and +t represents a region in which with a specific probability, all sets of samples of data are from the same population, and therefore are the same even though their means and sample variances appear to be different. The hypothesis that the sample mean is no different than the population mean is called the null hypothesis, H_0, and it is accepted or rejected by virtue of whether the sample mean lies within the interval of -t to +t. The confidence that the sample mean and the population mean are the same is 100(1-a) per cent. If T lies outside of the interval -t to +t, the null hypothesis must be rejected.

Student's-t statistic is tabulated for various degrees of freedom (d.f.). The tabulation must be entered with the d.f. and the confidence level to find the limits of the interval t to be used. For paired,

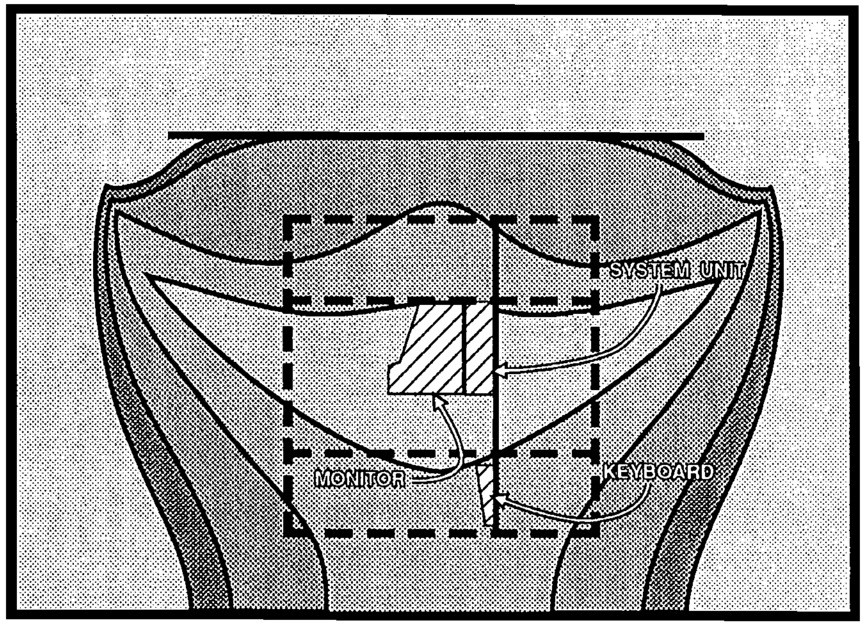

Figure 5. **PC System installed for V_{ZXY} measurement as seen from apex.**

related data, the d.f. are one less than the number of pairs of data; and for paired independent data, the d.f. are one less than the sum of the number in each set of sample data, *i.e.*:

$$m_x = n_x - 1, \; m_y = n_y - 1, \text{ and d.f.} = m_x + m_y.$$

Student's-t Statistic for *non-independent* (related) paired sample variables [9] was used for the first two sets of PC data since the same test object and configuration were used for measurements both in the GTEM! and on the OATS.

Student's-t Statistic for *independent* paired sample variables [10] was used for the first three sets of dipole data, since a different signal generator was used on the OATS from that used in the GTEM! measurement.

Test Series 1 - Dipole Testing

A series of three tuned dipole measurements were accomplished under slightly different circumstances. The three sets of measurements are as follows:

A set of measurements were performed using only tuned resonant dipoles covering the frequency range of 500 to 1000 MHz. The measurements were conducted at three distances, 3, 10 and 30 metres, corresponding to the three measurement distances common in international commercial EMC specifications. The measurements were made in a GTEM! and the field strength calculation was performed at the three measurement distances. The same dipoles were then transferred to the OATS and comparison measurements performed. The results of these measurements are shown in Tables I, II and III.

Table I
Tuned Resonant Dipole Measurements at 3 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
500.0	92.6	93.4	-0.8
600.0	92.3	93.7	-1.4
700.0	91.5	94.2	-2.7
800.0	90.4	92.2	-1.8
900.0	92.3	92.8	-0.5
1000.0	92.2	90.9	+1.4

The average difference between the GTEM! and the OATS is -1.97 dB, and the Standard Deviation is 1.39 dB

Table II
Tuned Resonant Dipole Measurements at 10 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
500.0	83.7	83.2	+0.5
600.0	82.1	83.6	-1.5
700.0	81.9	84.4	-2.5
800.0	80.6	82.2	-1.6
900.0	82.5	84.8	-2.3
1000.0	84.1	83.9	+0.2

The average difference between the GTEM! and the OATS is -1.2 dB, and the Standard Deviation is 1.26 dB.

Table III
Tuned Resonant Dipole Measurements at 30 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
500.0	74.0	73.3	+0.7
600.0	73.5	75.8	-2.4
700.0	72.4	72.6	-0.2
800.0	71.2	71.7	-0.5
900.0	73.0	73.4	-0.1
1000.0	74.6	73.3	+1.3

The average difference between the GTEM! and the OATS is -0.25 dB, and the Standard Deviation is 1.27 dB.

The second set of dipole measurements were made over the frequency range of 400 MHz to 1000 MHz. Tuned resonant dipoles were also used for this testing.

Table IV
Resonant Dipole Data, GTEM! vs OATS at 3 Meters

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
400.0	93.5	93.7	+0.2
500.0	93.7	92.9	-0.8
600.0	91.1	93.0	+1.9
700.0	89.8	92.2	+2.4
800.0	92.5	92.3	-0.20
900.0	90.3	93.7	+3.40
1000.0	90.3	91.9	+1.6

The average difference between the GTEM! and the OATS is +1.21 dB, and the Standard Deviation is 1.52 dB.

The third dipole test was performed in the same manner as the first, with the exception that an extended frequency range of the evaluation was desired. Where only resonant dipoles were used in the first evaluations, short dipoles were added to allow the extension of the evaluation down to 50 MHz. This was accomplished by tuning the resonant dipole to 230 MHz, and lowering the frequency of excitation in steps to 50 MHz. The dipoles were tuned to resonance at 230 MHz and above. The data is summarized in Table V. Note that these data were acquired with different instrumentation, at different test sites using a different GTEM!, making them an independent set of data.

Table V
Resonant Dipole Data, GTEM! vs OATS at 3 Meters

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
50.0	45.8	45.0	-0.8
100.0	69.3	73.1	+3.8
200.0	88.5	84.4	-4.1
230.0	96.0	88.7	+7.7
250.0	92.7	91.9	-0.8
300.0	99.8	97.3	-2.5
400.0	100.3	100.5	+0.2
500.0	101.3	100.7	-0.6
600.0	98.3	98.1	-0.2
700.0	99.7	96.8	-2.9
800.0	99.8	99.5	-0.3
900.0	100.2	97.3	-2.9
1000.0	99.6	97.3	-2.3

The average difference between the GTEM! and the OATS is -1.62 dB, and the Standard Deviation is 2.68 dB.

Test Series 2 - Personal Computer Testing

Test results for the testing of the two Personal Computer systems are shown in Tables VI, VII and VIII.

Table VI
Personal Computer System 1, OATS vs GTEM! at 3 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
35,32	64.4	63.6	+0.8
70.65	62.1	54.0	+8.1
141.5	45.2	45.2	+0.0
160.5	46.1	45.7	+0.4
186.1	45.0	38.4	+6.6

The average difference between the GTEM! and the OATS is +3.18 dB, and the Standard Deviation is 3.85 dB.

Table VII
Personal Computer System 1, OATS vs GTEM! at 10 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
35.3	54.4	57.7	-3.3
70.6	52.1	42. 8	+9.3
141.6	35.2	34.2	+1.0
160.5	36.1	35.0	+1.1
186.1	35.0	32.2	-2.8

The average difference between the GTEM! and the OATS is 2.18 dB, and the Standard Deviation is 4.57 dB.

Table VIII
Personal Computer System 2, OATS vs GTEM! at 3 Metres

Frequency (MHz)	GTEM! Correlated Field Data (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
140.0	28.74	27.5	+1.24
182.0	26.00	28.0	-2.00
185.0	30.20	28.6	+1.60
233.0	28.91	27.8	+1.11
320.0	24.69	27.6	--2.91

The average difference between the GTEM! and the OATS is -0.19 dB, and the Standard Deviation is 2.10 dB.

The data is summarized in Tables IX and X. Note that these data were acquired with different instrumentation, at different test sites using a different GTEM!, making them an independent set of data.

Discussion of Test Results

This section describes the results of the analysis performed on the data, and provides commentary about the results.

Results of Comparative Analysis

The test series reported show good agreement between GTEM! measurements and OATS measurements. It is interesting to note that the sets of dipole measurements, summarized in Table IX, show reasonably consistent results.

Table XI shows Pearson's correlation coefficient and the regression coefficients for the first three sets of dipole measurements and the first two sets of PC measurements. The correlation is good enough that, while these results came from measurements in which certain parts of the process were different, they can be combined with the rest of the data for further analysis.

Table IX
Summary of Dipole Measurements

Data Set	Average Difference (dB)	Standard Deviation (dB)
Dipole Data 1 at 3 Metres	-0.97	1.39
Dipole Data 1 at 10 Metres	-1.20	1.26
Dipole Data 1 at 30 Metres	-0.25	1.27
Dipole Data 2 at 3 Metres	-1.21	1.52
Dipole Data 3 at 3 Metres	+1.59	2.6

A similar summary for the personal computer data is shown in Table X.

Table X.
Summary of Personal Computer Measurements

Data Set	Average Difference (dB)	Standard Deviation (dB)
PC 1 at 3 Metres	3.18	3.85
PC 1 at 10 Metres	2.18	4.57
PC 2 at 3 Metres	0.19	2.09

The personal computer data is again in reasonably good agreement between the GTEM! and the OATS measurements. There is a difference between the first two data sets and the third that is in part attributable to the improvement in test procedures as the learning curve flattened. The last data set is felt to be representative of the measurement capability of the GTEM! much more than the first two.

As can be seen by comparing the data between Tables IX and X, there is a larger deviation in Personal Computer data and dipole data. This is felt to be related to the difference in the type of EUT from dipoles to a Personal Computer system. Dipoles are "strongly" polarized in that the two planes that are orthogonal to the plane of polarization show radiated emission levels that are low with respect to the primary plane. The Personal Computer system shows much smaller differences in the three orthogonal measurements. It is suspected that this difference as related to the characteristic of the personal computer array to radiate more equally in three orthogonal directions.

Results of Statistical Analysis

The general results of the statistical analyses are shown in Tables XI and XII.

Table XI
Correlation of Data from the First Three Dipole Measurements and First Two PC Measurements

Coefficient	Dipole 1 (Tables I, II, III)	PC 1 (Tables VI, VIII)
r	0.941	0.988
a	-2.36	+3.30
b	+1.00	0.95

Table XII shows the results of the Student's-t comparisons between the several sets of data and the null hypothesis test. D is the standard mean difference of the data sets, S_D is the standard deviation of the mean differences, t is the interval from the Student's-t distribution for a 95% confidence, and T is the deviation of the difference of the sample means from zero normalized to Student's-t distribution.

Table XII
Summary of Statistical Analysis on All Measurements
$\alpha = 0.05$, H_0: $\mu_D = 0$

Data Set	Dipole 1 (Tables I, II, III)	Dipole 2 (Table (IV)	Dipole 3 (Table V)	PC 1 (Tables VI, VII)	PC 2 (Table VIII)	All Dipoles	All PC's	All Data
D	-0.8	+1.2	-1.6	+2.7	-0.2	-0.7	+1.7	-0.02
S_D	2.7	2.3	7.2	4.0	4.4	4.5	13.6	8.1
n	36	7	13	10	5	38	15	53
d.f.	34	6	12	9	4	37	14	52
t	+/-2.030	+/- 2.447	+/- 2.179	+/- 2.262	+/- 2.776	+/- 2.029	+/- 2.145	+/- 2.008
T	-0.295	+1.388	-0.812	+2.107	-0.097	-0.980	+0.489	-0.022
H_0	Accept	Accept	Accept	Accept	Accept	Accept	Accept	Accept

Summary of Statistical Findings

The results show that there is no significant difference between the samples of data and we can accept the null hypothesis. That is, the GTEM! measurement is the same as the OATS measurement. The results also show that for the PCs, the field strength measured in the GTEM! without cable manipulation are essentially the same as those on the OATS with cable manipulation. This implies a much faster and more consistent measurement.

Measurement Error, Precision and Repeatability

The overall absolute rss error in the test instrumentation was 2.5 dB, and the probable instrumentation error was 1.7 dB. The precision of the measurement was 0.1 dB. From the descriptive statistics of the dipole-to-dipole OATS measurements, the probable variation of repeatability was 0.7 dB.

CONCLUSIONS

The following conclusions are drawn after the conduct of the testing described and after review and analysis of the test results.

Test Procedure Specific Conclusions

Must Control EUT Configuration - There are several issues connected with this statement. An early procedure tried for the three orthogonal rotations was to rotate each component in place. This was quickly discarded in favor of maintaining right relative positions of the components in an EUT like a Personal Computer System.

Must Manage Cable Placement - The relative positions of the interconnecting and power cables should be managed to maintain the EUT configuration to provide the highest levels of emanations from the EUT array.

Must Manage EUT Performance by Operating Software - The GTEM! may be scanned in frequency at rates much much higher than are normally associated with commercial EMC testing. The exercising software must be written with this in mind. For example, the optimal software approach in a GTEM! test is to write a single "H" to the screen and the printer, not a string of 80 "H's".

Must Use Precision Methods for Conduct of Measurements - The care that is normally taken by conscientious test personnel is adequate. For GTEM! to OATS testing it was found that it is necessary to characterize measurement accessories such as preamplifiers and coaxial cables to a precision of 0.1 dB, to achieve meaningful results.

More General Conclusions

Direct comparison of dipole and personal Computer measurements indicates a successful comparison measurement program.

Statistical analysis indicates comparison of GTEM! data and OATS data from a variety of devices and conditions indicates that the direct comparison is statistically valid.

The GTEM! is a viable alternative facility for the conduct of radiated emissions testing.

The time savings in the conduct of testing can be more than 8:1 in favor of the GTEM! This indicates that a higher test efficiency will allow substantially more testing to be done in the same amount of time, so long as this is possible in a practical sense.

The characteristics of the GTEM! allow its operation in a corporate location with a rather high electromagnetic ambient environment, rather than a remote site like a OATS. This allows increased efficiency in that travel time and possibly external test costs can be avoided. This makes the GTEM! ideal for EMC engineering development work.

The GTEM! will have future applicability as a qualification facility for new products. The amount of data collected to date has shown that the differences in GTEM! data and OATS data are not statistically different. Additional statistical data is probably needed to establish a larger data base, but it seems that this will be possible in the not too distant future.

Acknowledgements

The GTEM was developed by Asea Brown Boveri of Baden Switzerland, and is licensed for production by the Electro-Mechanics Co. The technical content of this paper was prepared for presentation at the 1991 IEEE EMC Symposium.

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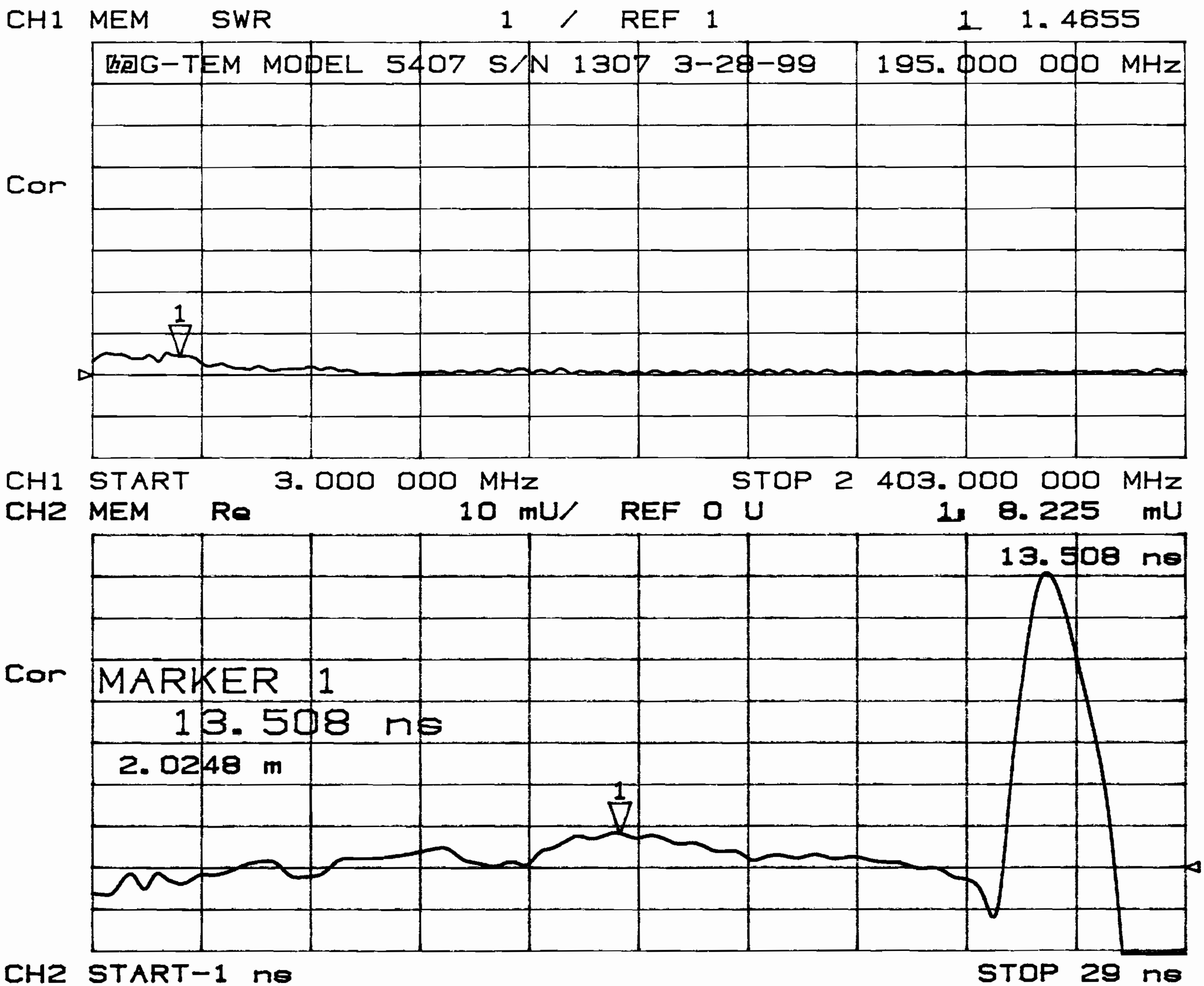
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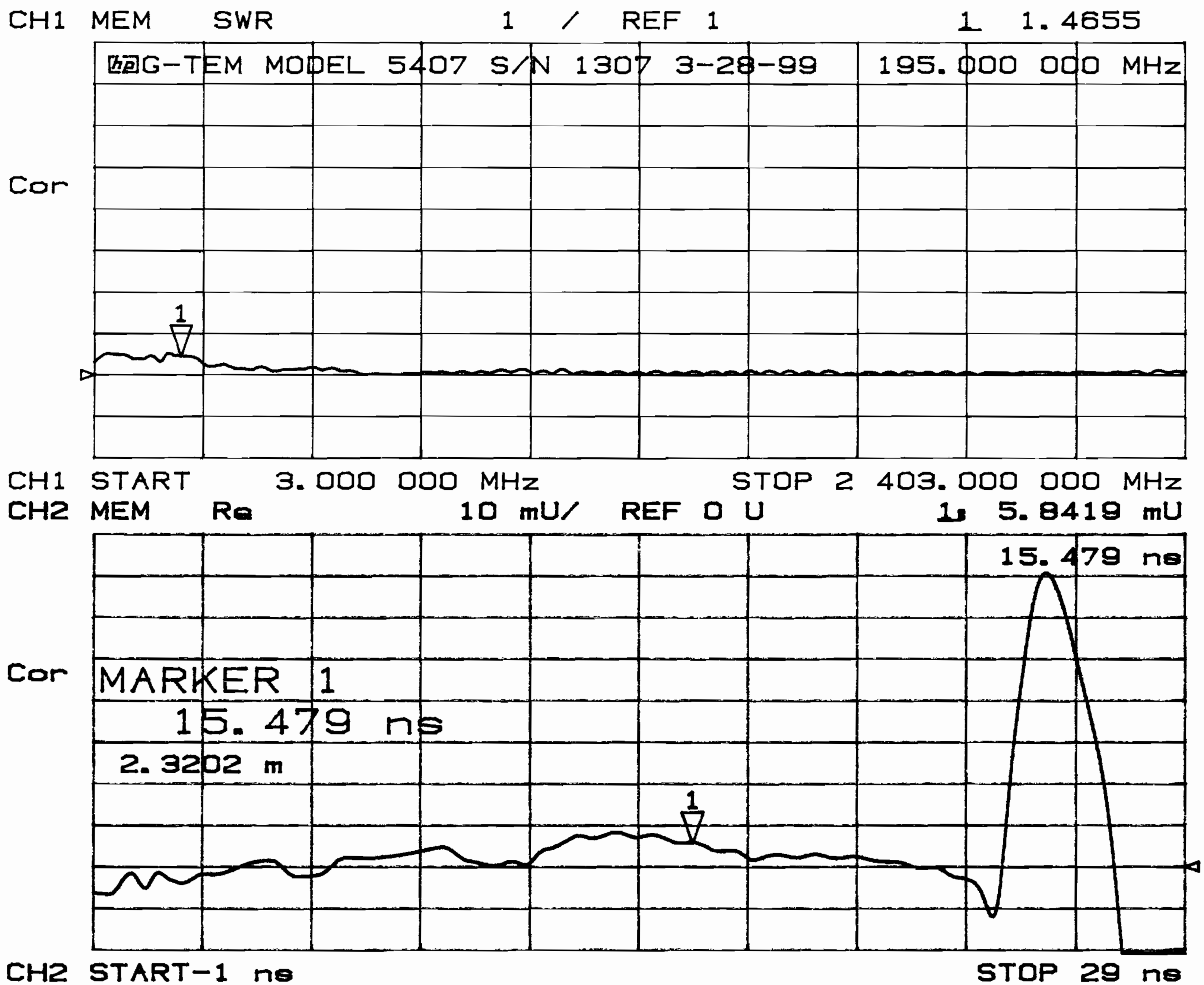
195.000 000 MHz
Cor
CH1 START 3.000 000 MHz STOP 2 403.000 000 MHz
CH2 MEM Re 10 mU/ REF 0 U 1 8.225 mU
13.508 ns
MARKER 1
13.508 ns
2.0248 m
CH2 START-1 ns STOP 29 ns


CH1 MEM SWR 1 / REF 1 1 1.4655
G-TEM MODEL 5407 S/N 1307 3-28-99
195.000 000 MHz
Cor
1
CH1 START 3.000 000 MHz STOP 2 403.000 000 MHz
CH2 MEM Re 10 mU/ REF 0 U 1 5.8419 mU
15.479 ns
Cor
MARKER 1
15.479 ns
2.3202 m
1
CH2 START-1 ns STOP 29 ns

GTEM Hyper-Rotated Fixture

By Martha Vela de Casillas
ROLM, A Siemens Company

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The use of the Gigahertz Transverse Electromagnetic (GTEM) Cell to conduct radiated emissions testing has lead to the development of new approaches to test EUTs (Equipment Under Test) which simplify the testing process, improve test correlation, and reduce the time required for testing. The hyper-rotated fixture is a result of the application of one of these new approaches. This fixture allows for test simplification, and good EUT and cable correlation. Its advantages over standard test methods and its design are explained in this paper.

Introduction

There is an increased interest in the use of the GTEM Cell to conduct EMC (Electromagnetic Compatibility) measurements. Radiated emission test correlation studies have demonstrated that correlation between the GTEM and the Open Area Test Site (OATS) is generally better than 4.5 dB for some frequencies, but better than 2.5 dB for most frequencies.[1] Low cost and test speed are two additional advantages making the GTEM a promising technology as an EMC test facility. In the GTEM cell, measurements are taken of the EUT while each of its three orthogonal axes is exposed. This requires the EUT to be positioned in the center of space.

Positioning the EUT in the center of space assumes that the EUT will function properly in non-typical orientations and requires extensive time to repeatedly test the EUT in the different orientations. A better test approach was introduced by Edwin Bronaugh.[2] This new approach allows for the EUT to be positioned on its typical orientation, and requires only simple rotation of the EUT to test it on each of its orthogonal axes. This new approach is based on the ortho-angle and ortho-axes which are the basis for the design of the GTEM hyper-rotated fixture.

Under this new approach, the EUT is oriented at a 54.7 degree angle from the centerline of the GTEM cell such that its projections on the vertical and horizontal planes containing the centerline are each at an angle of 45 degrees to the centerline. This positions the EUT and the GTEM cell at the ortho-axis. Rotating the EUT 360 degrees around this axis will then expose the radiated fields in the three orthogonal axes.

To understand this new approach, the ortho-angle and ortho-axes must be defined. The ortho-angle is defined as the unit field vector which has equal unit components on each of the orthogonal axes of a rectangu-

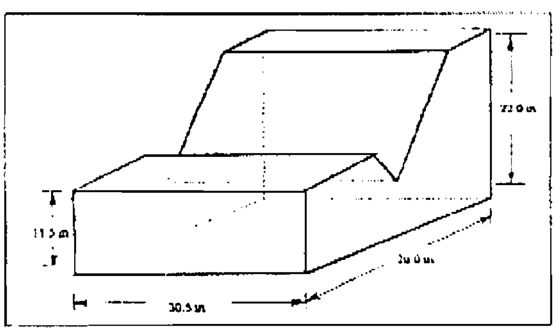


Figure 1. Hyper-rotated base.

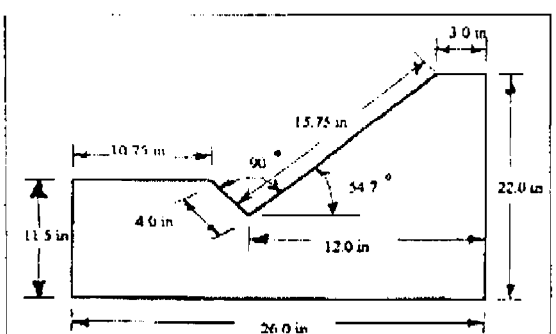


Figure 2. Hyper-rotated base, right side view.

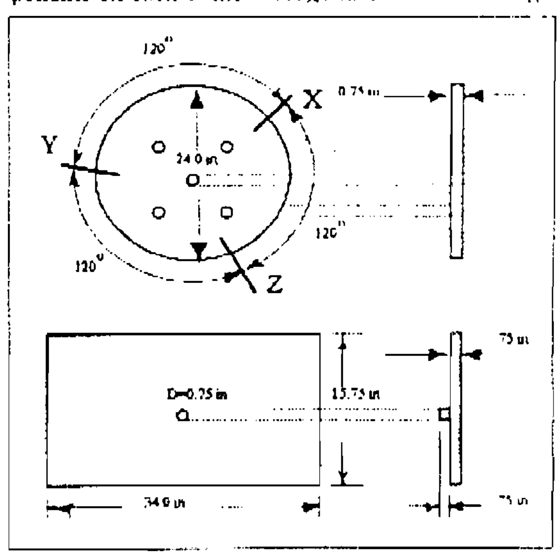


Figure 3. Turntable assembly.

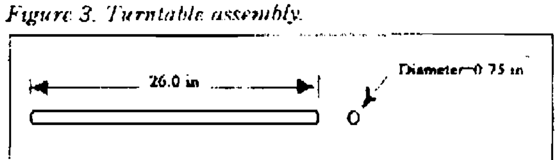


Figure 4. Cable guide.

GTEM Fixture

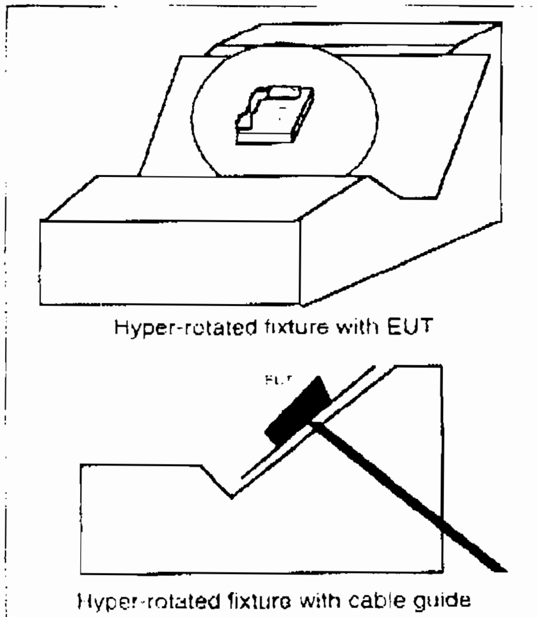


Figure 5. Hyper-rotated fixture with EUT.

lar coordinate system.[2] This field vector can be mathematically represented as:

$$|A| = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

If ax = ay = az , then

$$|A| = a\sqrt{3} \quad \text{or} \quad \frac{|A|}{a} = \sqrt{3}$$

Once the field vector |A| is determined, the ortho angle is calculated as follows:

$$\Theta = \operatorname{arcsec}\frac{|A|}{a}$$

$$\Theta = \operatorname{arcsec}\sqrt{3} = 54.7 \text{ degrees}$$

The angle between each axis and the unit vector is the ortho-angle and is equal to 54.7 degrees.

Another important definition is that of the ortho-axis. This axis lies on the diagonal of the cube that is formed by the field vector and each of the three unit components on each of the orthogonal axes. With these definitions in mind, the advantages of the hyper-rotated fixture are explained.

Advantages

The GTEM hyper-rotated fixture provides test repeatability and simplification, and good cable correlation. This fixture positions the EUT so that it remains in the same position while it is rotated 360 degrees around the ortho-axis, thus reducing the measurement variability between orientations. Once the EUT is positioned in the fixture, it is only required to rotate the circular platform of the fixture to the appropriate axis until all three orientations are tested. As a result, the test process is greatly simplified.

EUT functional failures are also less probable to occur with the EUT aligned with its gravity down vector, rather than aligning the EUT in non-typical orientations for testing. This alignment eliminates the probability of failures occurring during testing which could be caused by non-typical orientations affecting the EUT. This is one less variable to consider when evaluating electromagnetic interference (EMI) test results.

Another advantage of the hyper-rotated fixture is its cable correlation. The fixture keeps the EUT cable aligned with its ortho-axes and the GTEM cell. Aligning the cable with the ortho-axis results in the emissions being present at the field vector. Through each rotation of the hyper-rotated fixture, one of the three radiated emission readings is made. The correct reading of the cable's emissions results by calculating the vector sum from these readings. The resultant emissions can be expressed as follows:

$$|e_T| = \sqrt{e_x^2 + e_y^2 + e_z^2}$$

If $e_x = e_y = e_z$, then

$$|e_T| = e\sqrt{3} \quad \text{or} \quad e = \frac{|e_T|}{\sqrt{3}}$$

where, e_T = total emissions.

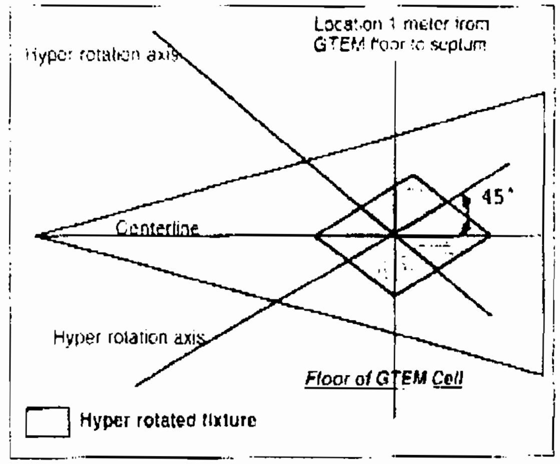


Figure 6. Top view of GTEM floor and hyper-rotated fixture.

Since the hyper-rotated fixture is positioned at the ortho-angle, the resultant emissions on the cable are $1/\sqrt{3}$ of the total emissions.

This results in cable emissions which are consistent on all three orientations, therefore achieving good cable correlation. Cables are one of the most critical factors to control in electromagnetic compatibility (EMC) measurements.

The GTEM hyper-rotated fixture also reduces the time required to test an EUT by only requiring the EUT to be rotated around its axis 120 degrees twice to complete a test. With the use of the GTEM cell (EMCO model 5311), the hyper-rotated fixture, and automated software, test results can be obtained in about 30 minutes. The hyper-rotated fixture design has been used for testing digital telephones and other electronic devices of similar dimensions during product development.

Mechanical Design

The mechanical design of the hyper-rotated fixture is composed of three main

GTEM Fixture

parts: a base unit, a turntable, and a cable guide. See Figures 1-4. The hyper-rotated fixture is made up of the following materials:

- Wood base unit
- Clear acrylic turntable
- Clear acrylic cable guide.

The most critical part in the design of the hyper-rotated fixture is the base unit. The base is the part that incorporates the ortho-angle into the design, see Figures 1 and 2. As can be seen, an angle of 54.7 degrees is formed where the turntable will be positioned.

The next piece forming the fixture is the turntable which consists of a circular platform and a rectangular base. When the circular platform is positioned on the rectangular base, it becomes a turntable. The circular platform is marked every 120 degrees using polar coordinates. This locates the EUT on the circular platform such that rotation of this platform 120 degrees twice will yield three orthogonal views to the GTEM.

The cable guide is the last piece of the fixture. It allows the external cables of the EUT to be routed in the same direction every time, simulating the cable drop required per ANSI C63.4 (American National Standards Institute) test methodology for EMC measurements. This guide axis.

The completed GTEM hyper-rotated fixture is shown in Figure 5. The right-side view of the fixture shows the position of the cable guide.

NOTE: DIMENSIONS GIVEN ARE for a 5311 GTEM, which is slightly Larger than the 5407 GTEM

Bill K.

Positioning of Hyper-Rotated Fixture in GTEM Cell

Once the fixture has been designed as described above, it must then be positioned in the GTEM Cell so that the hyper-rotated fixture projections on the vertical and horizontal planes containing the centerline are each at an angle of 45 degrees to the centerline of the GTEM. This will achieve proper exposure of the EUT emissions at the three orthogonal axes. See Figure 6.

Conclusions

The design of the hyper-rotated fixture is simple and provides major advantages in the EMC laboratory. This fixture reduces the time required to perform radiated emission tests by about 50 percent. The fixture simplifies EMC testing and also improves test repeatability. Finally, a key advantage achieved by the hyper-rotated fixture is its good cable correlation.

Deriving the design of the GTEM hyper-rotated fixture from the definition of the ortho-angle and ortho-axes has proven in the EMC laboratory that good cable correlation, significant test time reduction, test simplification and repeatability can be achieved in a GTEM cell.

References

1. H. Stephen Berger, "Radiated Emissions Test Correlation Between G-TEM, SAC, and OATS Facilities Using Digital Telephones," *Proceedings of The 1993 IEEE International Symposium on Electromagnetic Compatibility*, Dallas Texas, August 1993.

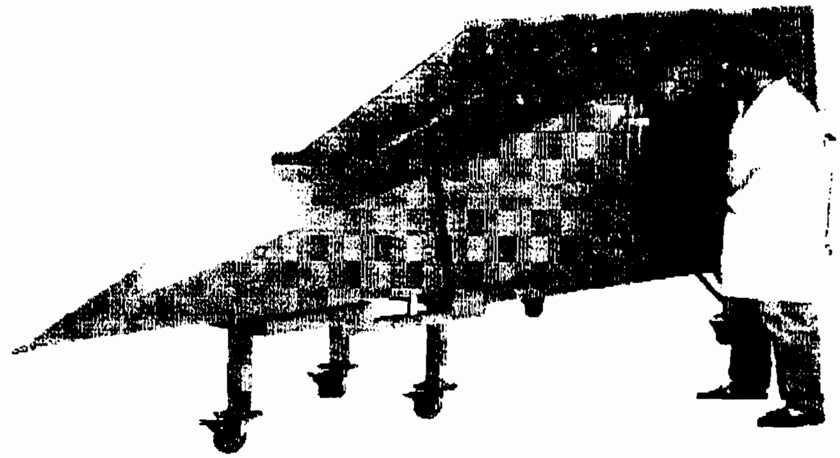
2. Edwin Bronaugh, "Simplifying EMI Immunity (Susceptibility) Tests in TEM Cells," *Proceedings of The 1990 IEEE International Symposium on Electromagnetic Compatibility*, Washington D.C., August 1990, pp. 488-491.

EMC TEST SYSTEMS, L.P. · An ESCO Company

GTEM!™ Model 5407

Features:

- New Size, Lower Priced
- 40x40x40 cm³ EUT Test Volume
- For All Phases of EMC Testing:
  - Design Qualification
  - Pre-Compliance
  - Full Compliance
  - Post Production
- For Full Compliance Demonstration of:
  - IEC 61000-4-3, EN 61000-4-3, MIL-STD 462, ANSI C63.4, EN 55022 and VDE 0871
- Reduces Test Time
  - ~ 8:1 for RE (vs. OATS)
  - > 2:1 for RI (vs. chamber)



Model 5407

EMCO's Model 5407 GTEM!™ enables users to perform radiated emissions and radiated immunity tests in less time than at either an OATS or in a chamber. Tests can be performed quickly and accurately throughout the product life cycle. Beginning with design qualification testing and moving through to pre-compliance testing, full compliance testing and production sampling. EMCO's Model 5407 GTEM! is a time-saving device for your test lab. A typical radiated emissions test (10,000 point scan) can be completed in 15 minutes or less, while a typical radiated immunity test can usually be completed in half the normal time.

The GTEM! is based on experience, not experimentation. Originally developed in the EMC Baden (Switzerland) labs of ABB, the cell has been accepted in the EMC community for more than 10 years and is field proven daily at more than 400 installations worldwide. Measurements made with a GTEM! are accepted for final compliance demonstration by the FCC for Part 15 & 18 radiated emissions testing, and comply with IEC 61000-4-3 Annex D for immunity testing.

The GTEM!'s unique tapered shape, offset septum, resistive termination network and absorber-lined backwall remove performance limitations of TEM cells and boxy enclosures. Electromagnetic wave and RF current termination are smooth and controlled. Field uniformity is ± 3 dB up to 1 GHz, and ± 4 dB above 1 GHz.

EMCO's new Model 5407 is the result of an on going program of research and development. The new size is a result of customer requirements, while the lower price is a result of process and material improvements.

Standard Configuration

- GTEM! cell with door placement on right side (viewed from feed)
- Mobile base with locking caster wheels
- Hydraulically damped door with recessed contact mechanism, contact RF sealing and shielded window
- Rantec high performance RF anechoic absorber
- Single phase, 20A, 50/60 Hz filter with choice of two floor mounted receptacles
- One wall mounted fiber optic feedthrough (4 lines)
- Three N connector feedthroughs

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RF Emissions/Immunity Test Cell
GTEM! Model 5407

Electrical Specifications

MODEL	FREQUENCY RANGE	VSWR TYPICAL	VSWR MAXIMUM	MAXIMUM CW INPUT POWER	INPUT IMPEDANCE	FEED CONNECTOR TYPE	SHIELDING EFFECTIVENESS
5407	RE TESTS 9 kHz 5 GHz[2] RI TESTS DC 20 GHz[2]	CHARACTERISTIC FREQ[1] < 1.6:1 ALL OTHER FREQ < 1.3:1	CHARACTERISTIC FREQ[1] < 1.75:1 ALL OTHER FREQ < 1.50:1	100 W	50 W	CW 7/16 DIN to N ADAPTER	FROM INTERNAL E-FIELDS 80 dB MINIMUM 10 kHz 1 GHz

[2] ... correlation to OATS established:
3 Position GTEM OATS
Correlation Algorithm, 30 MHz – 5 GHz
9 Position GTEM OATS
Correlation Algorithm, 9 kHz 5 GHz

[1] Characteristic Frequency:
The frequency at which cross-over between the primary termination of the resistor load boards and the RF absorber occurs.

Physical Specifications

MODEL	OUTER CELL W/ BASE DIMENSION[1]	DOOR DIMENSION	HIGHEST ACCURACY TRANSVERSE TEST SURFACE IN CENTER OF CELL	APPROX CELL WEIGHT	MAXIMUM SEPTUM HEIGHT[2]	DISTRIB LOAD RATING[3]
5407	(L) 4.00 m (13.10 ft) (W) 2.16 m (7.08 ft) (H) 2.06 m (6.75 ft)	(W) 686 mm (27.0 in) (H) 747 mm (29.4 in)	(W) 400 mm (15.75 in) (H) 400 mm (15.75 in)	500 kg 1100 lb	900.0 mm 35.4 in	430 kg 950 lb

[1] Cell height without base: Model 5407 - 1.4 m (4.6 ft)

[2] Measurement taken at rear of test volume

[3] Total EUT load distributed at a maximum loading of 450 kg/m²

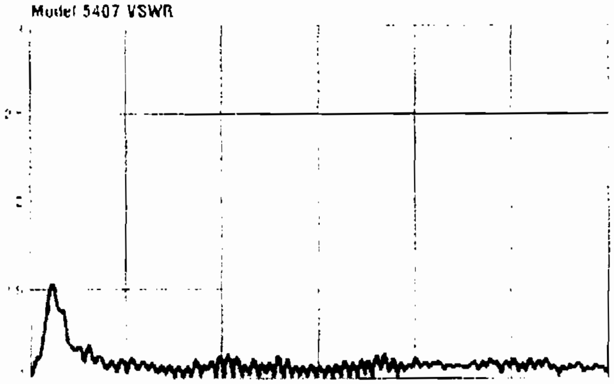
Point loads less than 7 cm² should not exceed 20 kg/cm².

Note. As standard, the unit is shipped partially assembled with instructions for installation. Doorways that are 218.5 cm (86 in) wide and 203.2 cm (80 in) high are needed for subassembly passage. If space limitations exist, the unit can be shipped unassembled. Contact EMCO sales department regarding requests to ship the unit unassembled and for supervision of installation.

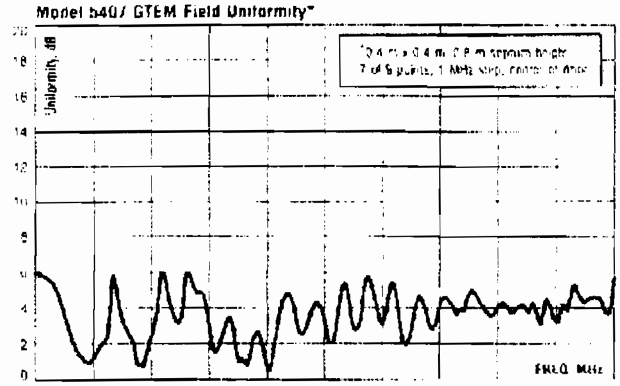
Options

- Custom electrical filters
- Custom feedthrough panels
- EUT XYZ axis positioning device
- EUT illumination
- Forced ventilation

Model 5407 VSWR



Model 5407 GTEM Field Uniformity*



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